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Petrological Studies on the Ryôke Metamorphic Rocks in the
Toyone-mura Area, Aichi Prefecture,
Japan*

By

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Contents

	Page
Abstract	50
I. Introduction	51
II. Historical review	51
III. Geological situation of the Ryôke zone	53
IV. Geological setting of the Toyone-mura area	54
V. Geology	54
1. General statement	
2. Ryôke complex	
3. Geological structure of the Ryôke complex	
4. Shitara Tertiary system	
5. Shitara Tertiary volcanic rocks	
VI. Plutonic rocks.....	60
1. Cortlandtite	
2. Gabbroic rocks	
3. Granitic rocks	
VII. Metamorphic rocks	65
1. General statement	
2. Zonal mapping	
3. Sedimentogeneous metamorphic rocks	
A) Original rocks	
B) Chemical compositions	
C) Mineral assemblages and variations	
D) Petrography	
4. Metamorphic rocks derived from basic igneous rocks	
A) Original rocks	

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	B) Chemical compositions	
	C) Mineralogical compositions	
	D) Petrography	
VIII.	Mineralogy of metamorphic minerals.....	79
	1. General statement	
	2. Quartz	
	3. Potash feldspar	
	4. Plagioclase	
	5. Muscovite	
	6. Biotite	
	7. Garnet	
	8. Cordierite	
	9. Andalusite and sillimanite	
	10. Hornblende and cummingtonite	
	11. Tourmaline	
	12. Oxide and sulfide minerals	
	13. Other minerals	
IX.	Metamorphic conditions	93
	1. General statement	
	2. Mineral parageneses and metamorphic facies	
	3. Andalusite to sillimanite transition	
	4. Muscovite breakdown	
	5. Garnet-cordierite-biotite equilibria	
	6. Petrogenetic grid	
	7. Other physical conditions	
	8. Contact metamorphism	
	9. Retrogressive metamorphism	
X.	Geological situation of the Ryôke zone viewed from petrological aspects	102
XI.	Summary and conclusions	103
	Acknowledgements	104
	References	104

Abstract

The Ryôke metamorphic rocks in the Toyone-mura area, Aichi Prefecture are described in regard to their mode of occurrence, petrography, chemistry and mineralogy. Physical conditions of the Ryôke regional metamorphism are discussed from the viewpoints of mineralogical equilibria and the nature of the constituent minerals.

The metamorphic terrain of this area can be divided into three progressive zones based on the mineralogical variations in the pelitic rocks. The metamorphic rocks are characterized by the mineral association of cordierite-K-feldspar, and the metamorphic reactions of andalusite-sillimanite transition and muscovite breakdown in pelitic ones.

The Ryôke regional metamorphism can be regarded as the result of the general upheaval of iso-geotherm intimately connected with the vast granitic intrusions. The geological situation of the Ryôke zone is referred its special character to the metamorphism which had occurred in the ascending part of the Honshû geosyncline during or continued from the time preceeding to the metamorphism.

I. Introduction

The Ryôke zone is one of the axial belts of the geologic structure of Southwest Japan. It occupies the inner periphery of the Median Tectonic Line which is one of the major tectonic lines in Japan. This zone is composed of vast granitic intrusives and their associated metamorphic rocks, derived mainly from sedimentary and slightly from basic igneous rocks. The time of the regional metamorphism and the granitic intrusions are regarded to be late Mesozoic Era; the isotopic ages determined with various granitic and metamorphic rocks are concentrated almost in the late Cretaceous period. From the geologic evidences, however, the metamorphism and the pre-Nôhi granitic intrusions are generally considered by many geologists to have occurred in late Jurassic to early Cretaceous.

Therefore, to the geological situation of the Ryôke zone and its role in "Honshû geosyncline" the special attention should be paid. And also, the problem of mutual relation between the plutonism and the metamorphism in the Ryôke zone, and the late Mesozoic acid igneous activities typical in Southwest Japan, is necessary to be solved.

In this paper, the nature of the Ryôke regional metamorphism will be discussed from the petrological point of view which came from the studies on the rocks in the Toyone-mura area, Aichi Prefecture. Since the summer of 1967, the author has pursued the geological and petrological studies on the metamorphic rocks as well as the plutonic rocks of this area. Prior to this, the author presented some preliminary reports on the general geology and petrology of some specific rocks of this area (KUTSUKAKE, 1970, 1974, 1975a, 1976), but those seem to be incomplete. In this respect, full descriptions and discussions of the geology and petrology of those metamorphic rocks will be given herein.

II. Historical Review

The name "Ryôke" was first adopted by HARADA (1890) to a series of gneisses having common features, as "Riokeschiefer" (Ryôke schist and gneiss). But, his usage has no means to show any geological units in the Japanese Islands. In those days, the granitic and metamorphic rocks in the Ryôke zone as well as those of the Abukuma plateau were regarded to be Precambrian in age. Thereafter, the evidence of the transition from the Ryôke metamorphic rocks to the nearly non-metamorphic Palaeozoic formations was confirmed by ISHII, then it became to be considered that the Ryôke zone was formed by the orogenesis undergone from late Palaeozoic to early Mesozoic (SUGI, 1933). Summarizing the geohistory of the Japanese Islands, KOBAYASHI (1941) proposed the opinion that the Ryôke zone as well as the Sambagawa and the Mikabu belts are the axial part of his Sakawa orogenesis of late

Mesozoic, and it corresponds to the pliomagmatic zone of this orogenic belt. In his monumental work on the granitic and metamorphic rocks in the Dando-san area, Aichi Prefecture, KOIDE (1949, 1958) recognized the polymetamorphism and classified the granitic intrusive rocks into two types: the "older intrusives" and the "younger intrusives", and also the metamorphic rocks into the "older Ryôke metamorphics" and the "younger Ryôke metamorphics". Moreover, he insisted that metasomatism played an important role during the Ryôke regional metamorphism and plutonism. Since his work the classification of the Ryôke granitic rocks into the "older" and the "younger" groups became rather routine.

After the World War II, many investigators worked in the fields of the Ryôke zone to study the general geological and petrological problems, especially of granitization and metamorphism. In these circumstances the opinions opposing to KOBAYASHI's appeared, as GORAI (1952, 1955) and YAMASHITA (1957), that the Ryôke zone was formed by the "Honshû orogeny" of late Palaeozoic to early Mesozoic.

On the metamorphic rocks mineralogical studies and structural analysis were carried out in many areas, such as Komagane (HAYAMA, 1956, 1959a, 1960, 1962a, 1964a, b), northern Kiso range (ÔKI, 1961a, b; KATADA, 1965, 1967), Kasagi (NAKAJIMA, 1960; HARA, 1962), Mitsue (SUWA, 1956, 1961) and the Yanai district (OKAMURA, 1960; NUREKI, 1960). Metamorphic zoning based on not lithological features but mineralogical variations was first attempted by HAYAMA (*op. cit.*) in the Komagane area. Nature of the progressive metamorphism has been elucidated by HAYAMA, KATADA, ÔKI and SUWA, and recently by ONO (1969b). The type of the Ryôke metamorphism is known to the world as a representative andalusite-sillimanite type facies series by MIYASHIRO (1961). He regarded first the metamorphism of the central Abukuma plateau to be typical of it, later he (1973) amended his opinion and stated that the metamorphism in the Takatô area of the Ryôke zone is the representative of the type.

In 1960's the isotopic age determinations on the granitic and metamorphic rocks in the Ryôke zone were made by both K-Ar and Rb-Sr methods and other methods (MILLER *et al.*, 1961; SHIBATA *et al.*, 1962; BANNO and MILLER, 1965; KARAKIDA *et al.*, 1965; ISHIZAKA, 1966; HAYASE and ISHIZAKA, 1967; OZIMA *et al.*, 1967; SHIBATA and HAYAMA, 1968; UENO *et al.*, 1969; and others). Almost all of the data are concentrated between 60 and 100 m.y. and no apparent distinction between the "older" and the "younger" granites can be recognized in this sense. Obviously the "post-Nôhi granites" form the volcano-plutonic association with the Nôhi rhyolites, which are the representative acid volcanic rocks of late Mesozoic igneous activities (YAMADA and NAKAI, 1968; RYÔKE RESEARCH GROUP, 1972), but, the age of the Ryôke regional metamorphism and the "pre-Nôhi granites" is not settled as yet (YAMADA, 1971; RESEARCH GROUP FOR THE RYÔKE BELT, 1975).

III. Geological Situation of the Ryôke Zone

The Ryôke zone ranges from the south of the Suwa basin in Nagano Prefecture to the Kunisaki peninsula of Kyûshû for about 700 km in length with width of 30 to 50 km (Fig. 1). It is composed mainly of plutonic rocks from ultrabasic (cordierite) through basic and intermediate to granitic, and metamorphic rocks derived from sedimentary and basic igneous rocks. The granitic rocks occupy the far wider extension than the metamorphic rocks. Wide distribution of metamorphic rocks is known in several areas, such as; northern Kiso range, Komagane area, Dando area and Mikawa plateau in the Chûbu district, Kasagi area in the Kinki district and the Yanai district. In other areas, the metamorphic rocks are sporadically distributed in the granites as xenolithic masses and/or roof-pendants.

The metamorphic rocks grade into the non-metamorphic sedimentary rocks of late Palaeozoic to early Mesozoic in the inner side of the Ryôke zone. Therefore, the original rocks are probably the equivalents to the sedimentary rocks of the Tanba-Mino belt.

On the other hand, in the inner side of the Ryôke zone, the late Mesozoic acid igneous rocks are widely distributed, of which the most famous are the Nôhi rhyolites of effusives and the Naégi-Agematsu granites of intrusives in the Chûbu district.

Bounded by the Median Tectonic Line, the Ryôke zone adjoins with the Sam-

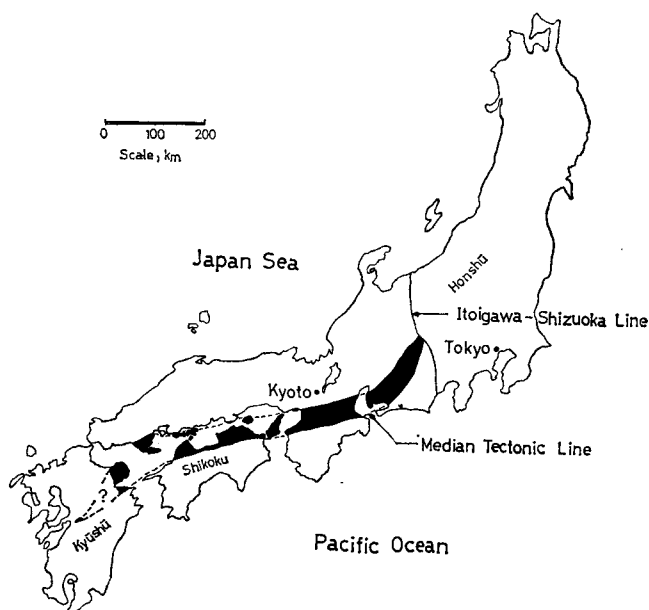


Fig. 1. Distribution of the Ryôke metamorphic terrain (dark shaded).

bagawa metamorphic belt which is characterized by glaucophanitic (blue schist facies) regional metamorphism. As regard to the parallel arrangement of these two contrasting metamorphic belts, several implications for the genesis have been proposed; one of the representatives is the idea of "paired metamorphic belts" by MIYASHIRO (1961). However, the genetical relations between them are not certainly revealed so far, partly because of the uncertainty of the age of the Sambagawa metamorphism at present.

IV. Geological Setting of the Toyone-mura Area

In central Japan (=Chûbu district), studies on the Ryôke zone have been made from the various points of view. Based on the accumulated data, recently very excellent geological maps were compiled by RYÔKE RESEARCH GROUP (1972) and YAMADA *et al.* (1974). Simplified geological map from YAMADA *et al.* is shown in Fig. 2.

The Toyone-mura area occupies the southeastern part of the Ryôke zone of the Chûbu district. This area belongs to the high-grade zone of the Ryôke regional metamorphism, namely the sillimanite zone, and is characterized by the occurrence of a large mass of metabasite. Over the Shitara* Basin, the classic Dando area (KOIDE, 1949, 1958) is situated. In both the areas, several geological and petrological common features can be recognized.

V. Geology

1. General statement

Toyone-mura area is composed mainly of the Ryôke complex and Tertiary sediments and their associated volcanic rocks, so-called "Shitara Tertiary volcanics".

General geology of this area has been reported since 1890's (MIURA, 1898; NÔTOMI, 1924; YAMADA *et al.*, 1972). However, detailed geological and petrological studies on the Ryôke complex have not been made before the present author's investigation, except the geological maps by SAKAKIBARA (1967, 1968) covering a part of the area. HAYAMA *et al.* (1963) carried out the study on the mylonitic rocks along the Median Tectonic Line of this area and its surroundings.

As to the Shitara Tertiary complex, YOSHIDA (1953) and KATÔ (1955, 1962) carried out the stratigraphical studies, and the geological map was compiled by KATÔ for all over the basin. On the other hand, the Shitara Tertiary volcanics have not been fully investigated, only petrochemical studies have been made by KUNO (1960, 1968) and NAGASHIMA (1953).

* Strictly speaking "Shitara" is proper, but "Sidara" or "Shidara" is in general use.

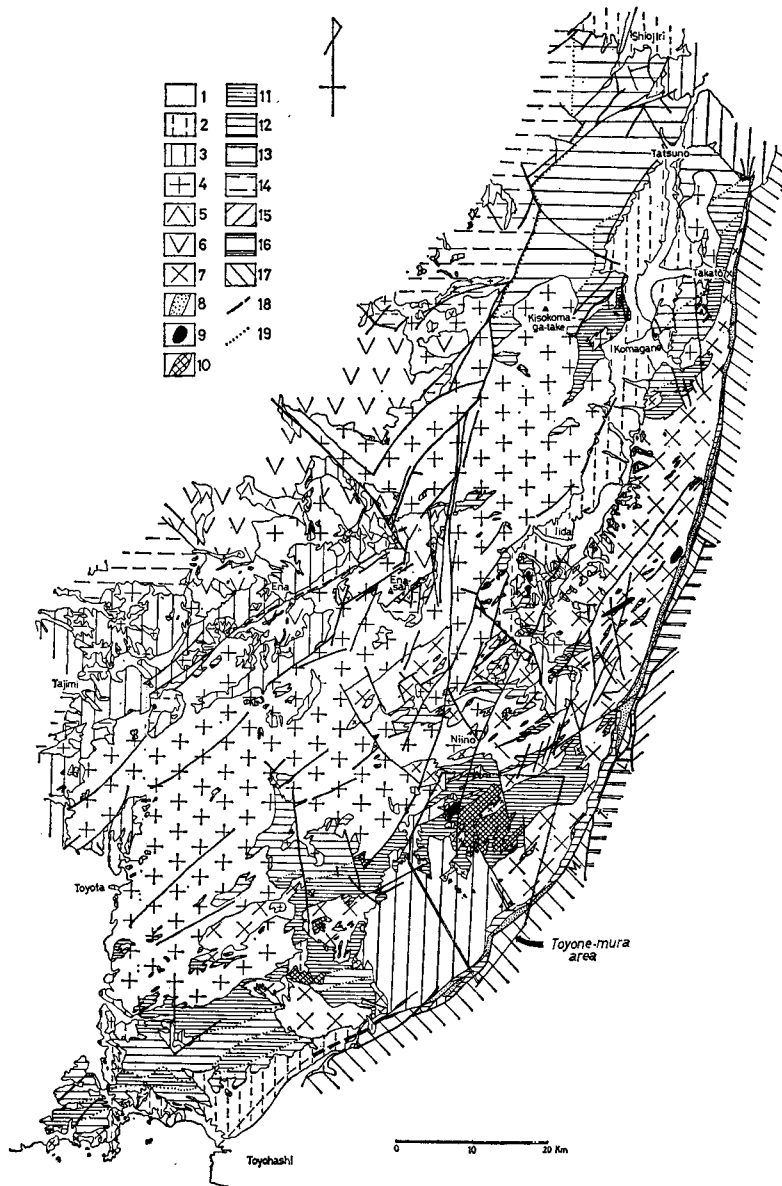


Fig. 2. Geological sketch-map of the Ryôke zone of the Chûbu district, simplified from YAMADA *et al.* (1974).

1. Alluvium, 2. Terrace and fan deposits, 3. Neogene system, 4. Post-Nôhi granites,
5. Granite porphyry, 6. Nôhi rhyolites, 7. Pre-Nôhi granites, 8. Mylonites, 9. Gabbros and cortlandtite, 10. Metabasites, 11. The sillimanite zone, 12. The cordierite zone, 13. The biotite zone, 14. Non-metamorphic zone, 15. Shimanto formation, 16. Chichibu formation, 17. Sambagawa crystalline schists, 18. Fault, 19. Boundary between metamorphic zones.

Geological Map of the Toyone-mura Area,
Aichi Prefecture, Japan

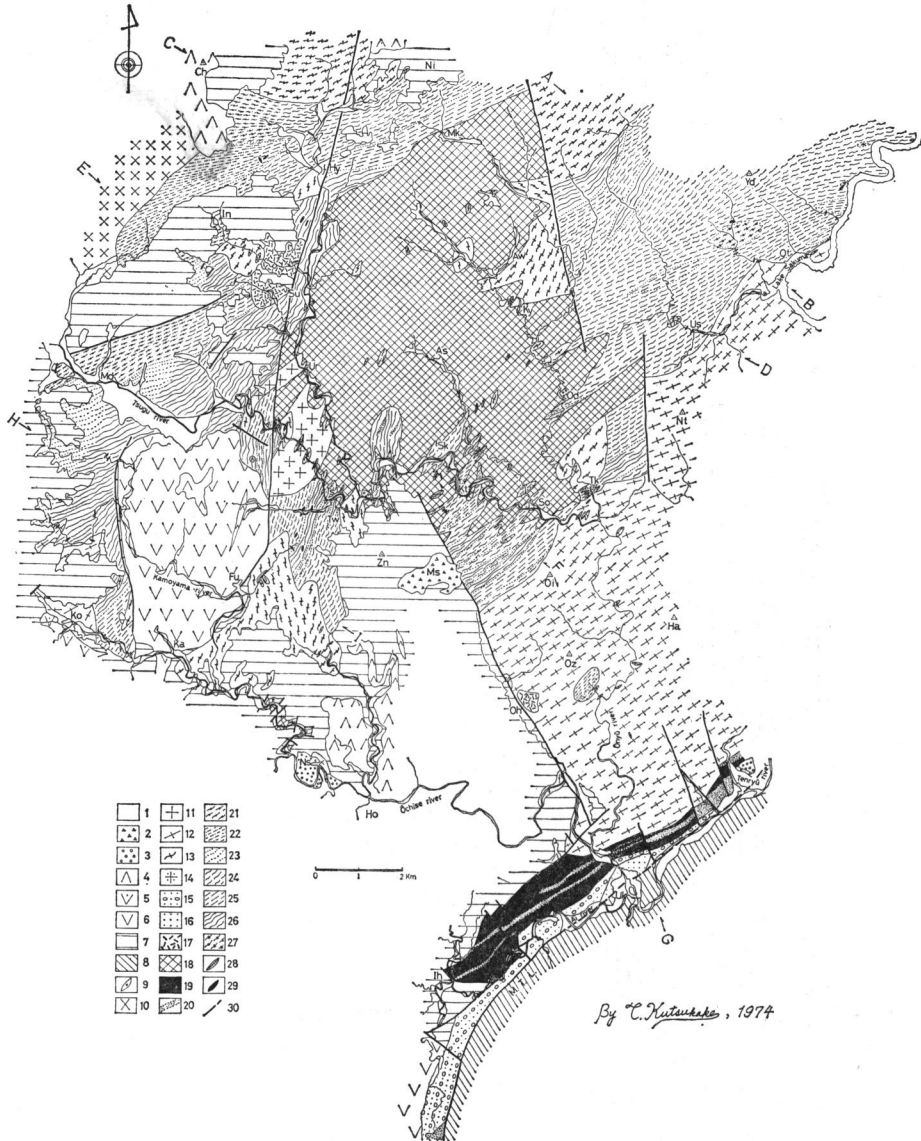


Fig. 3. Geological map of the Toyone-mura area.

1. Alluvium, 2. Debris, 3. Terrace deposit, 4. Basalt and andesite, 5. Dacite, 6. Rhyolite, 7. Tertiary sediments, 8. Sambagawa schists, 9. Busetsu granite, 10. Inagawa granite, 11. Mitsuhashi granite, 12. Tenryûkyô granite, 13. Kamihara

Preliminary reports of the geology of this area have already been presented (KUTSUKAKE, 1970, 1974, 1975, 1976). Geological map is shown in Fig. 3.

2. Ryôke complex

The Ryôke complex is composed mainly of several kinds of granitic intrusives and the metamorphic rocks derived from sedimentary and basic igneous rocks. Besides the granitic rocks the basic intrusive rocks such as gabbros occur as small masses.

In the central part of the area, a large mass of metabasite of dolerite origin is distributed (KUTSUKAKE, 1975a). The granitic intrusives are classified into the following five types; the Kamihara quartz diorite, the Tenryûkyô granite, the Mitsuhashi granite, the Busetsu granite and the Inagawa granite from older to younger. The Kamihara quartz diorite is found as sheet-like masses in the gneisses and it is also intruded into the metabasites. The Tenryûkyô granite occupies the southeastern part of the area as a batholith body. The Mitsuhashi granite is invaded into both the metamorphic rocks and the Kamihara quartz diorite as small stock-like mass. The Busetsu granite occurs as narrow dykes at some places. In the western margin of the area, the Inagawa granite is distributed and it extends to the west and continues to the Sumikawa granodiorite of the Dando area (KOIDE, 1958; NAKAI, 1970, 1974).

Four masses of gabbroic rocks are found, three of which have been already reported (KUTSUKAKE, 1974). A small mass of cortlandtite occurs in the gneiss, northwest to Ôtani village of Tomiyama-mura.

The sedimentogeneous metamorphic rocks are distributed from the northwestern to the central part of the area, and extend into the Hiraoka area, east to the mapped area. Along the Median Tectonic Line, narrow belt of hornfels exists. Besides these, small xenolithic and roof-pendant-like masses of sedimentogeneous metamorphic rocks are found abundantly in the granites. They are originated from shales,

quartz diorite, 14. Fine-grained biotite granodiorite, 15. Mylonite, 16. "Hällefinta", 17. Gabbro, 18. Metabasite, 19. Hornfels (pelitic and psammitic), 20. Hornfels derived from chert, 21. Mica schist (pelitic), 22. Mica schist (psammitic), 23. quartz schist, 24. Gneiss (pelitic), 25. Gneiss (psammitic), 26. Quartz gneiss, 27. Nebulitic gneiss, 28. Metamorphic rock derived from "Schalstein", 29. Marble, 30. Fault.

M.T.L. Median Tectonic Line.

Locality name As: Asakusa, Aw: Awase, Ch: Chausu-yama, Fu: Futto, Ha: Hanare-yama, Ho: Hongô, Hy: Hiyosawa, Ih: Ichihara, In: Inoshikori, Ka: Kami-Awashiro, Ko: Kobayashi, Kt: Kakinotaira, Ky: Kashiyage, Md: Midashi, Mk: Makino-shima, Ms: Misono, Ni: Niino-tôge, Ns: Naka-Shitara, Nt: Nihonka-tsuka-yama, Od: Ôdachi, Oh: Ôhata, Oi: Ôiwa-dake, Os: Ôsawa, Ot: Ôtani, Oz: Ôzasa-yama, Sk: Shimo-Kurokawa, So: Sogawa, Su: Sakauba, Tk: Tashika, Ts: Tsugawa, Tw: Tawagane-tôge, Uk: Urakawa, Ur: Ure, Us: Urushijima, Yd: Yatsudake-yama, Zn: Zinno-yama.

sandstones and chert alternating with one another in various scales. In the western part those of chert origin predominate. Rarely small lens-like masses of limestone and basalt are intercalated in them.

In contact with the Median Tectonic Line, mylonitic rocks are developed with width of 50 m to 500 m. According to HAYAMA *et al.* (1963), the mylonites are derived from quartz dioritic intrusive rocks which can be correlated with the Hiji quartz diorite in the Komagane area (HAYAMA, 1959b).

3. Geological structure of the Ryôke complex

To trace the foliations of gneisses and granites and the schistosity of mica schists and quartz schists, the geological structure of this area was established.

The general trend of this area is NE-SW, which is in accordance with the general trend of the Ryôke zone in the Chûbu district. Examining in detail, local structural variations can be ascertained;

Part	Trend
Northeastern	E-W~N70°E
Northwestern	E-W~N70°W
Central	N-S
Southeastern	N45°E
Southwestern	N30°~45°E

Dips generally incline to N to NE with variable angles. Synclinal structure is recognized north to Urushijima and south to Tsugawa, and the former is in NE-SW and the latter in N-S in direction respectively.

The Kamihara quartz diorite and the Tenryûkyô granite are structurally harmonic and concordant to the surrounding metamorphic rocks (Plate I-1). On the other hand, the Mitsuhashi granite discordantly cuts both the metamorphic rocks and the Kamihara quartz diorite.

Structural map is shown in Fig. 4, and the cross-sections are in Fig. 5.

4. Shitara Tertiary system

In the central part of the Shitara Basin, volcanic rocks of mainly rhyolitic composition are widely distributed. And at the margins of the basin, Tertiary (Miocene) sediments are developed. According to KATÔ (1962), the Tertiary system of the basin can be divided into two groups: the upper Hokusetsu group and the lower Nansetsu group. In this area only the upper group is distributed, and it consists of sandstone, mudstone and conglomerate alternated with one another. Structurally they are almost horizontal, although slightly dipping toward the centre of the basin.

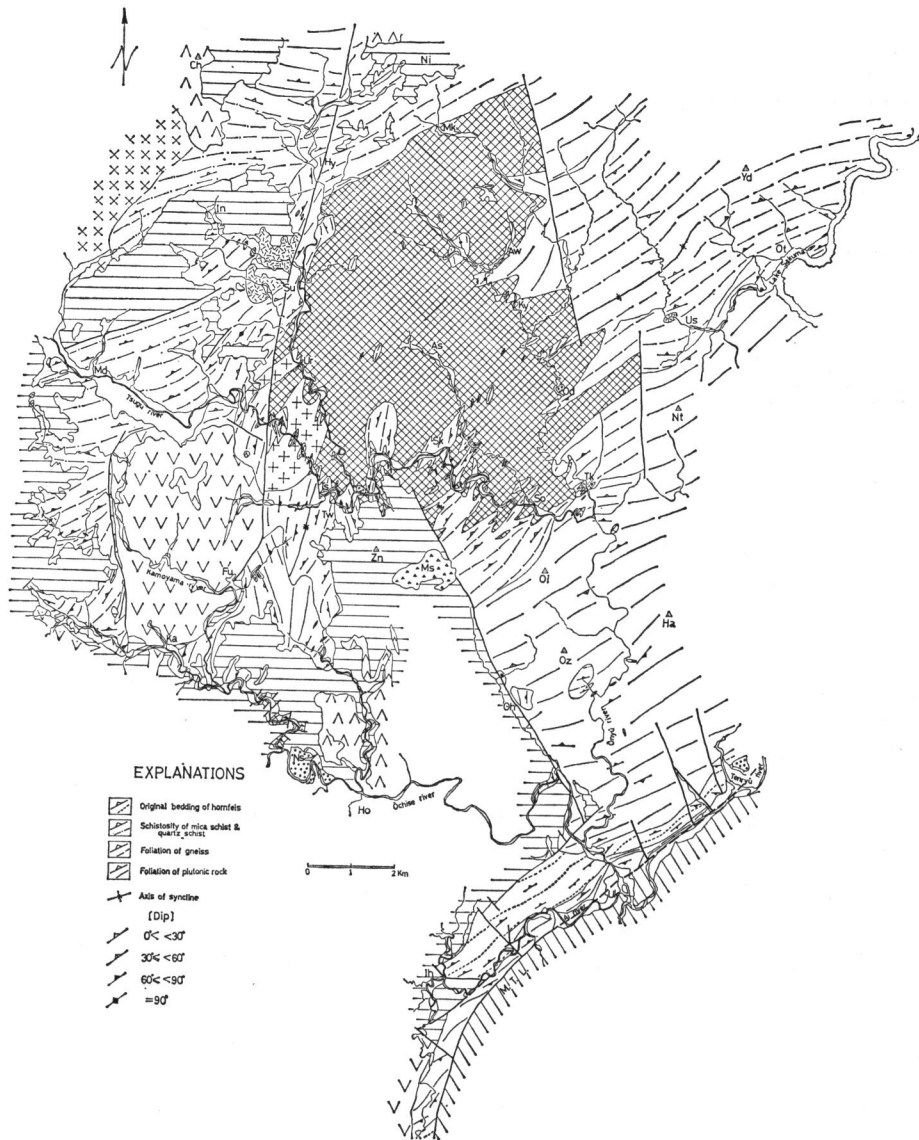


Fig. 4. Structural map of the Toyone-mura area.
The other symbols are the same as those of Fig. 3.

5. Shitara Tertiary volcanic rocks

The volcanic complex in the Shitara Basin has been called "Shitara Tertiary volcanics" which belongs to the Setouchi volcanic province of Miocene age. The studies on the volcanic rocks are very rare, thus their nature is scarcely known.

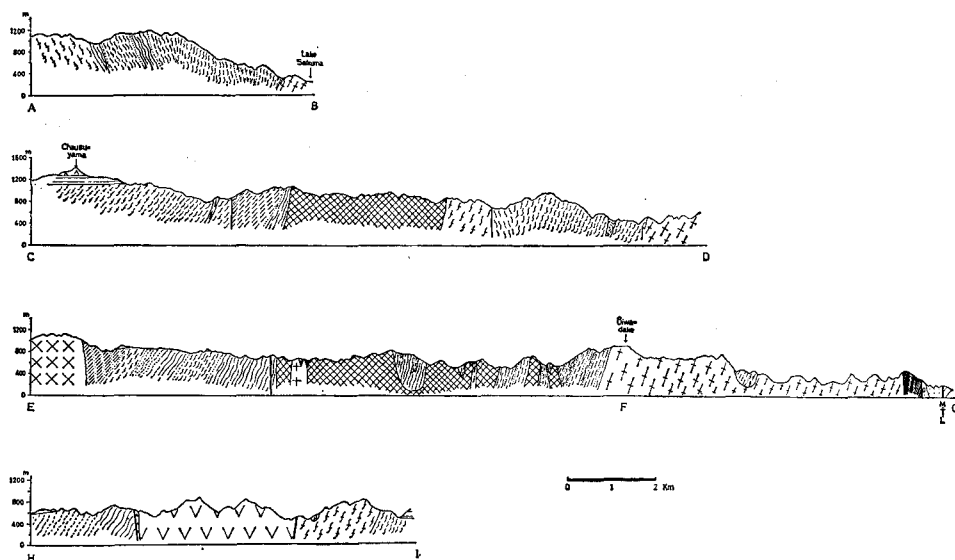


Fig. 5. Cross-sections. Legend: see Fig. 3.

They are probably composed of rhyolitic to dacitic tuffs, welded tuffs and lavas.

Dacitic and rhyolitic dykes, intimately connected with the above mentioned volcanics, cut the Tertiary sediments as well as the Ryôke complex. Andesite occurs as lava flows and domes at such places as Chausu-yama and Maru-yama, etc.

Basaltic dykes and sheets of both alkali basalt and high-alumina basalt cut the other rocks and the Tertiary sediments (KUNO, 1960, 1968). Frequently they form dyke swarms, typically appearing south to Tsugu (KUNO, 1954, pp. 95–96). Differentiated mugearite sheet at Oidaira was briefly described by KUNO (1968).

VI. Plutonic Rocks

1. Cortlandtite

About 1 km northwest to Ôtani village of Tomiyama-mura, there occurs a small mass (3 m × 7 m) of cortlandtite in stock-like form intruding into the gneiss. Detailed description and genetical discussions of this rock will be given in a separate paper (KUTSUKAKE, 1977).

2. Gabbroic rocks

Three masses of gabbroic rocks in the Toyone-mura are already reported (KUTSUKAKE, 1974). Another mass of gabbro was found at Urushijima of Tomiyama-mura, and it will be described in some detail.

The present mass occupies about 150×350 square metres, occurring in the gneiss. The gabbroic rocks have suffered metamorphism, and now are meta-gabbros composed mainly of plagioclase, hornblende, biotite and quartz, of quartz dioritic mineral composition. Petrography of the typical rock types is given below;

“Hornblende gabbro” (Specimen No. 73081303)

This rock is medium-grained, dark greyish coloured and massive.

Under the microscope, it shows hypidiomorphic-granular texture. Mafic minerals form decussate aggregate, which typically occurs in thermal metamorphic rocks (SPRY, 1969). It is composed mainly of plagioclase, hornblende, biotite and quartz, with small amounts of apatite, zircon and ores.

Plagioclase is hypidiomorphic tabular and polysynthetically twinned. It shows two-layered zoning with a very calcic uniform core (\sim An96) and a margin (An68–72), bounded rather distinctly. It is clouded due to the presence of fine dusty materials scattered all over the grain. Streak-like anti-perthite, now replaced by muscovite, is observable.

Hornblende seems to have replaced the original mafic minerals (probably pyroxene). It forms above-mentioned aggregate with biotite, and partly replaced by biotite. Frequently ragged hornblende crystals are observed. It has exsolution lamellae parallel to (001). Optical properties are as follows; $(-)\ 2V=80^\circ$; $c \wedge Z=20^\circ$; $\gamma=1.671$; $X < Y < Z$; X=nearly colourless~very pale yellow, Y=pale greenish brown, Z=light greenish yellow.

Biotite forms aggregate by alone and/or with hornblende. It is pleochroic with X=nearly colourless, Y=Z=light brown, and has $\gamma=1.647$.

Quartz is interstitial and invades other minerals, suggesting its later development. It has been probably released when pyroxene was replaced by hornblende.

“Hornblende leuco-gabbro” (Specimen No. 73081302)

This rock is medium-grained, light greyish coloured and massive. Except that this rock is rich in modal plagioclase, it is very similar to the above described one.

Plagioclase is not so calcic and of compositions An73–76. *Hornblende* has $(-)\ 2V=84^\circ$ and $\gamma=1.685$. *Biotite* has $\gamma=1.656$.

3. Granitic rocks

As already mentioned, in this area five types of granitic intrusive rock occur. Petrography and chemical compositions have been given in another paper (KUTSU-KAKE, 1970). Here, some additional data of petrography and chemical compositions are presented, especially of the Kamihara quartz diorite and the Mitsuhashi granite.

a) The Kamihara quartz diorite

Rock types and sampling localities of the described specimens are shown in

Table 1. List of the described specimens of the Kamihara quartz diorite

No.	Specimen No.	Rock type	Locality
1*	68050407	Medium-grained, gneissose horn.-biot. granodiorite	Tsugawa
2*	68050410	Medium-grained, gneissose horn.-biot. tonalite	Kingoshi
3*	69112603	Medium-grained, weakly gneissose horn.-biot. tonalite	2 km. east to Ōshima, Tsugu-mura
4*	69121405	Coarse-grained, weakly gneissose horn.-biot. tonalite	Tashika
5*	70051601	Medium-grained, weakly gneissose garnet-bearing biot. granodiorite	Hiyosawa
6*	70051603	Medium-grained, gneissose horn.-biot. tonalite	1 km. northeast to Misawa
7	70051501	Medium-grained, gneissose biot. tonalite	Nakamura
8	70082401	Medium-grained, gneissose horn.-biot. quartz diorite	Fukawa
9	70112104 72090815	Fine-grained, gneissose garnet-bearing biot. granodiorite	Inoshikori
10	71032501	Medium-grained, gneissose horn.-biot. tonalite	Kami-Awashiro

*: Analyzed specimen.

Table 2. Modal compositions of the Kamihara quartz diorites in the Toyone-mura area (Vol. %)

No.	1	2	3	4	5	6	7	8	9	10
Plagioclase	54.5	56.8	54.0	50.5	39.4	56.0	49.1	59.1	39.9	49.1
Potash feldspar	8.4	1.5	5.6	0.9	19.9	1.4	4.5	2.5	20.1	2.6
Quartz	21.2	21.8	18.6	18.6	28.2	31.0	28.8	14.3	26.3	16.6
Biotite	11.1	14.9	15.8	20.7	12.3	10.1	18.0	15.7	11.7	17.1
Hornblende	4.8	5.0	5.9	7.4	—	1.4	—	8.1	—	14.0
Others	—	—	—	1.7	0.2	0.2	Mus. 0.2 0.4	0.2	Gar. 0.1 Op. 0.2 Non-op. 1.5	0.5

Mus.=muscovite, Gar.=garnet, Op.=opaque minerals, Non-op.=non-opaque minerals.

Table 1. Modal compositions are shown in Table 2, and they are plotted in the diagrams of quartz-K-feldspar-plagioclase and of total mafics-quartz plus K-feldspar-plagioclase, together with those of other areas (Fig. 6). Essentially they belong to tonalite field, partly to quartz diorite and granodiorite fields. The optical properties of the main constituent minerals are shown in Table 3.

b) The Mitsuhashi granite

Rock types and sampling localities of the described specimens are shown in Table 4, with their modal compositions. Optical properties of the main constituent

Table 3. Optical properties of main constituent minerals of the Kamihara quartz diorites

No.		1	2	3	4	5
Plagioclase	n_1	1.546-1.551	1.549-1.551	1.551-1.552	1.550-1.553	1.542-1.544
	An %	36-45	42-45	45-47	44-48	28-32
Hornblende	α	1.644	1.644	...	1.652	
	γ	1.670	1.672	...	1.677	
	(-) $2V$	73°	73°	...	79°	
	$c \wedge Z$	18°	19°	22°	18°	—
	X	yellow brown	yellow	pale yellow	yellow	
	Y	brownish green	pale brownish green	pale yellow green	pale yellow green	
Z	grass green	pale brown green	brownish green	yellow green		
Biotite	γ	1.648	1.643	1.644	1.636	1.655
	X	pale yellow	pale yellow	pale yellow	pale yellow	pale yellow
	Y=Z	dark brown	brown	brown	brown	deep brown
No.		6	7	8	9	10
Plagioclase	n_1	1.549-1.550	1.544-1.546	1.548-1.550	1.543-1.546	1.550-1.551
	An %	42-43	32-36	41-43	30-36	44-46
Hornblende	α	1.655				1.650
	γ	1.682				1.676
	(-) $2V$	72°				74°
	$c \wedge Z$	19°	—	altered	—	16°
	X	pale yellow green				pale yellow green
	Y	grass green with brownish tint				pale green
Z	brownish green				pale brownish green	
Biotite	γ	1.657	1.653	1.650	1.658	1.652
	X	pale yellow	yellow	pale yellow	pale yellow	pale yellow
	Y=Z	deep brown	reddish brown	reddish brown	reddish brown	brown

...: not determined.

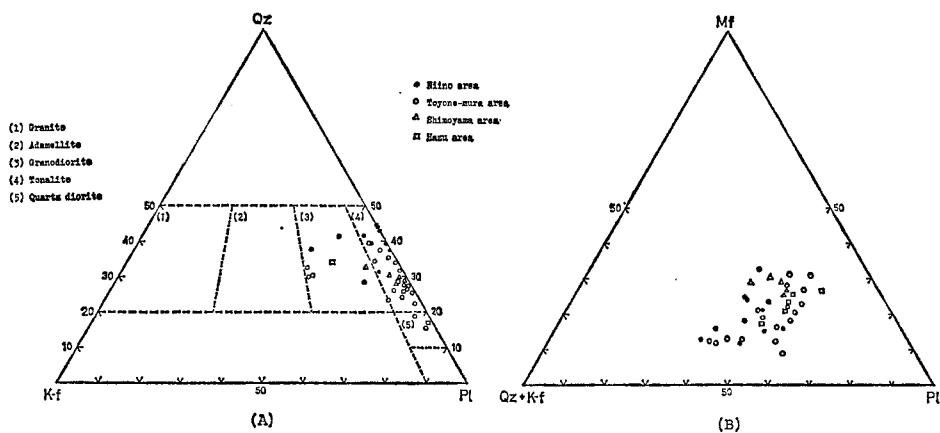


Fig. 6. (A) Modal quartz-potash feldspar-plagioclase diagram, (B) Modal total mafics-quartz plus potash feldspar-plagioclase diagram, of the Kamihara quartz diorite in the Ryôke zone of the Chûbu district.

Qz: quartz, K-f: potash feldspar, Pl: plagioclase, Mf: total mafics.

Table 4. Modal compositions of the Mitsuhashi granites in the Toyone-mura area (Vol. %)

	1	2	3	4	5
Plagioclase	59.5	43.6	42.4	26.1	44.4
Potash feldspar	1.6	19.1	29.4	40.9	1.6
Quartz	30.1	28.0	19.6	30.2	48.1
Biotite	7.1	5.6	8.3	2.9	5.8
Hornblende	1.2	3.4	—	—	—
Others	0.6	0.6	0.2	0.0	0.1
Total	100.1	100.0	99.9	100.1	100.0

	Specimen No.	Rock type	Locality
1.	68050312	Medium-grained hornblende-biotite tonalite	500 m. south to Nakadaira
2.	69121301	Fine-grained hornblende-biotite granodiorite	500 m. west to Tsugawa
3.	68050304	Medium-grained biotite adamellite	1 km. north to Nakadaira
4.	68032311	Medium-grained biotite granite	Nakadaira
5.	68032309	Medium-grained garnet-bearing biotite trondhjemite	Near Nakadaira

Table 5. Optical properties of main constituent minerals of the Mitsuhashi granties

		1	2	3	4	5
Plagioclase	n_1	1.540-1.549	1.542-1.544	1.537-1.543	1.535-1.540	1.536-1.544
	An %	23-43	25-32	18-30	15-23	16-32
Biotite	γ	1.659	1.666	1.657	1.663	1.665
	X	v.p. yellow	p. yellow	p. yellow	v.p. yellow	p. yellow
	Y=Z	yellowish brown	dark greyish brown	orange brown	yellowish brown	yellow brown
Hornblende	α		1.680			
	β		1.697			
	γ		1.702			
	(-)2V	altered	54°	—	—	—
	$c \wedge Z$		16°			
	X		p. greenish yellow			
	Y		greyish green			
	Z		green			

p.=pale, v.p.=very pale. Numbers correspond to those of Table 4.

minerals are shown in Table 5.

Some additional chemical analyses are shown in Table 6.

Full description of petrography of the granitic rocks in the Ryôke zone of the Chûbu district will be given in a monograph (HAYAMA *et al.*, in preparation).

VII. Metamorphic Rocks

1. General statement

Metamorphic rocks are divided into two major varieties as regard to their original rocks; sedimentary and basic igneous rocks. In this chapter, nature of the original rocks is discussed and petrography will be given in terms of zonal mapping.

2. Zonal mapping

This area can be divided into three zones representing progressive mineralogical changes in pelitic and psammitic metamorphic rocks. They are denoted as Zones I, IIa and IIb. The zonation is shown in Fig. 7.

3. Sedimentogeneous metamorphic rocks

A) Original rocks

The original rocks are shales (slates), sandstones and chert with scarce inter-

Table 6. Chemical compositions and C.I.P.W. norms of the granitic rocks in the Toyone-mura area

	Kamihara quartz diorite		Mitsubishi granite
	(a)	(b)	(c)
SiO ₂	62.43	67.31	72.33
TiO ₂	0.62	0.45	0.34
Al ₂ O ₃	16.46	15.50	14.52
Fe ₂ O ₃	1.07	0.50	0.80
FeO	4.67	3.38	2.26
MnO	0.05	0.06	0.03
MgO	2.40	1.38	0.38
CaO	4.88	2.72	2.73
Na ₂ O	3.26	3.95	3.37
K ₂ O	1.82	3.32	1.63
H ₂ O(+)	0.88	0.63	0.74
H ₂ O(-)	0.29	0.12	0.13
P ₂ O ₅	0.18	0.15	0.06
Total	99.01	99.47	99.32
C.I.P.W. Norms			
Q	19.90	21.82	38.88
C	0.69	0.82	2.39
or	10.75	19.62	9.63
ab	27.59	33.42	28.52
an	23.03	12.51	13.15
en	5.98	3.44	0.95
fs	6.76	5.16	2.98
mt	1.55	0.72	1.16
il	1.18	0.85	0.65
ap	0.42	0.35	0.14
water	1.17	0.75	0.87
Total	99.02	99.46	99.32

(a) Specimen No. 70051603

Anal. T. KUTSUKAKE

(b) Specimen No. 70051601

(c) Specimen No. 69121301

calation of limestone lenses and basalt. They are alternated with one another in some decade centimetres to tens of metres in thickness (Plate I-3). In the eastern and central parts, shales and sandstones are predominant, on the other hand, in the western half chert is the most abundant in the original rock.

It is very difficult to establish the stratigraphic succession for all over the area, as the metamorphic rocks are separated into several blocks by the granitic invasions. Therefore, for each part the stratigraphic column was made so far as possible (Fig. 8).

Abnormal sedimentary facies is developed in some horizons and has been preserved even after the metamorphism. As a case aluminous pelitic part with ir-

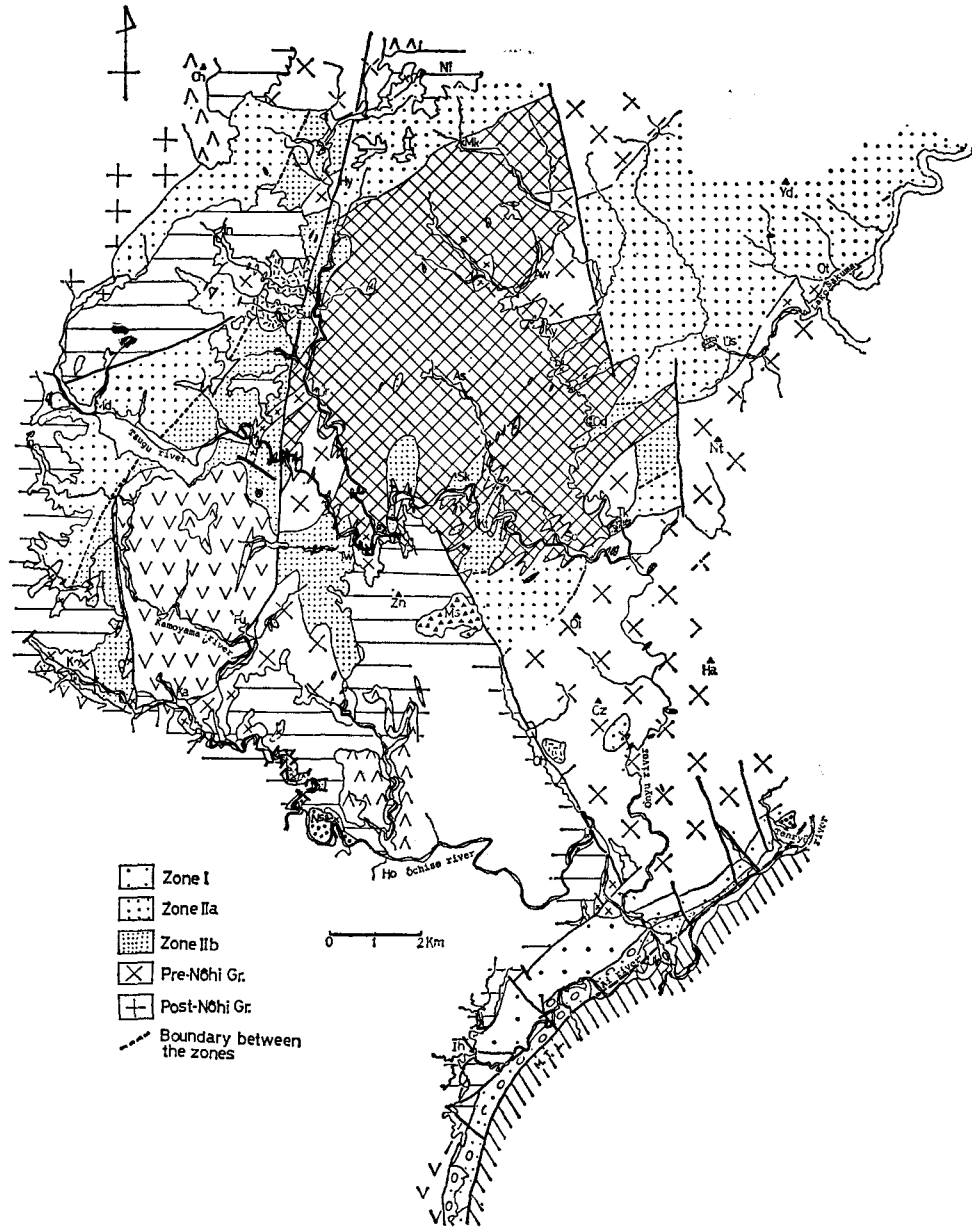


Fig. 7. Metamorphic zones in the Toyone-mura area.

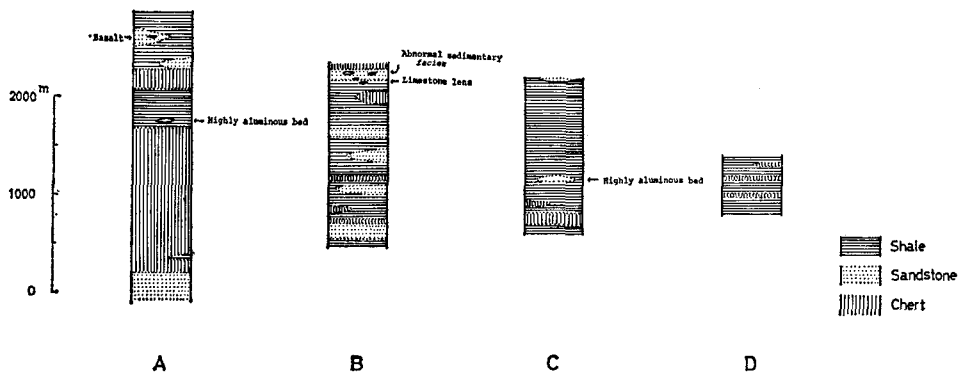


Fig. 8. Columnar sections of the metamorphic rocks in regard to their original rocks.
 A. Western part
 B. Central part
 C. Northern part
 D. Eastern part

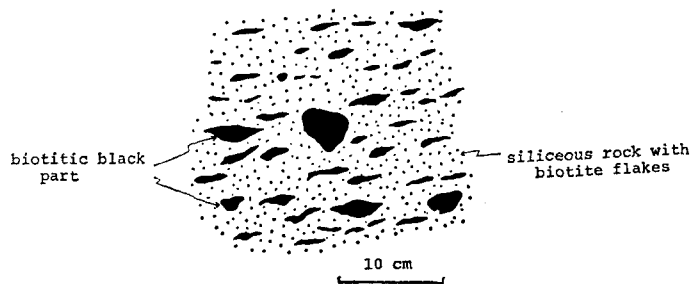


Fig. 9. Abnormal sedimentary facies preserved even after the metamorphism.

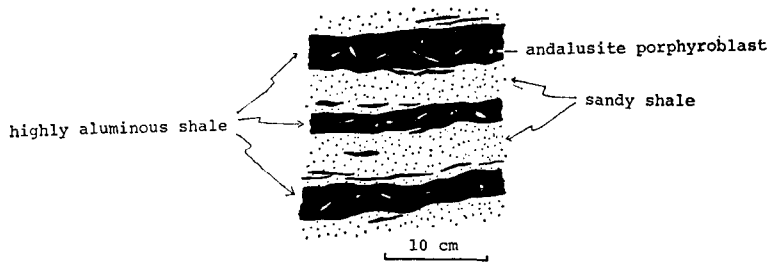


Fig. 10. Mode of occurrence of highly aluminous beds.

regular form of about 5 cm in diameter are scattered in siliceous sandy matrix (Fig. 9). The similar sedimentary facies has been reported from the northern Kiso range (KATADA *et al.*, 1959). In another case, highly aluminous bed occurs as thin layers alternated with sandstone (Fig. 10). This is the sole mode of occurrence of highly aluminous rocks observed in the Ryôke metamorphic terrain (HAYAMA, 1960).

B) Chemical compositions

Chemistry of the sedimentogeneous metamorphic rocks has already been reported (KUTSUKAKE, 1970, 1976). Summing up the characteristic features of chemistry of these rocks, the following statements can be justifiably presented;

(a) The compositions of the rocks have not been drastically changed during the metamorphism, except for the volatile components, and they have essentially preserved their original compositional characters.

(b) Chemical compositions of these metamorphic rocks are very similar to their non-metamorphic equivalents in the northern Kiso range, except that they are slightly rich in lime.

(c) In comparison with the average abundances of minor elements in pelitic rocks, they are characterized by rich in Co, poor in Cr, Ni, and Sr, and rather same in V, Cu, Zn, and Rb.

AKF-plots are made after the procedure by ESKOLA (1915) (Fig. 11).

C) Mineral assemblages and variations

Representative mineral assemblages of each zone are as follows;

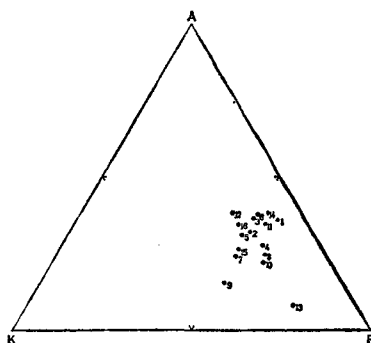


Fig. 11. AKF diagram for pelitic and psammitic metamorphic rocks in the Toyone-mura area.

$$\begin{cases} A = \text{Al}_2\text{O}_3 + \text{Fe}_2\text{O}_3 - (\text{Na}_2\text{O} + \text{K}_2\text{O}) \\ K = \text{K}_2\text{O} \\ F = \text{FeO} + \text{MnO} + \text{MgO} \end{cases}$$

The numbers of analyses correspond to those of Table 3 of KUTSUKAKE (1976).

(1) Zone I

a) Pelitic and psammitic rocks

- Quartz-potash feldspar-plagioclase-biotite-muscovite-cordierite
- Quartz-plagioclase-biotite-muscovite-garnet
- Quartz-plagioclase-biotite-muscovite
- Quartz-potash feldspar-plagioclase-biotite-muscovite
- Quartz-plagioclase-biotite-muscovite-cordierite-andalusite

Tourmaline, graphite, iron ores, apatite and zircon are common accessories.

b) Siliceous rocks

- Quartz-plagioclase-biotite-muscovite-garnet
- Quartz-potash feldspar-muscovite
- Quartz-muscovite

Tourmaline, ores, apatite and zircon are common accessories.

(2) Zone IIa

a) Pelitic and psammitic rocks

- Quartz-potash feldspar-plagioclase-biotite-muscovite-cordierite-sillimanite
- Quartz-potash feldspar-plagioclase-biotite-muscovite-cordierite-andalusite
- Quartz-plagioclase-biotite-muscovite-andalusite-sillimanite
- Quartz-potash feldspar-plagioclase-biotite-muscovite-cordierite
- Quartz-plagioclase-biotite-muscovite-sillimanite
- Quartz-potash feldspar-plagioclase-biotite-cordierite-andalusite-sillimanite

Accessories are the same as those of Zone I.

b) Siliceous rocks

- Quartz-plagioclase-biotite-muscovite-garnet
- Quartz-potash feldspar-plagioclase-biotite-muscovite

(3) Zone IIb

a) Pelitic and psammitic rocks

- Quartz-potash feldspar-plagioclase-biotite-muscovite-cordierite-sillimanite
- Quartz-potash feldspar-plagioclase-biotite-muscovite-sillimanite
- Quartz-plagioclase-biotite-muscovite-cordierite
- Quartz-plagioclase-biotite-muscovite-cordierite-garnet

As accessories, graphite, iron ores, tourmaline, apatite and zircon occur.

b) Siliceous rocks

- Quartz-plagioclase-biotite-muscovite-garnet
- Quartz-potash feldspar-plagioclase-muscovite-garnet
- Quartz-potash feldspar-plagioclase-biotite-muscovite
- Quartz-potash feldspar-plagioclase-biotite
- Quartz-potash feldspar-plagioclase-muscovite
- Quartz-plagioclase-biotite-muscovite

Zone	I	IIa	IIb
Quartz			
Potash feldspar	-----		
Plagioclase (An %)	15 - 25	20 - 35	25 - 35
Muscovite			
Biotite			
Cordierite	-----		
Pyralspite		
Andalusite		-----	
Sillimanite		-----	
Tourmaline		-----	
Graphite		-----	

----- : abundant
 ----- : common
 : rare

Fig. 12. Mineralogical variations in pelitic and psammitic metamorphic rocks in the Toyone-mura area.

Table 7. Modal compositions of several sedimentogeneous metamorphic rocks (Vol. %)

Zone	IIa				IIb				
	No.	1	2	3	4	5	6	7	8
Quartz		49.0	25.2	56.5	56.1	37.5	36.8	45.1	54.6
Potash feldspar		1.0	10.4	5.1	4.5	1.0	2.3	1.3	0.9
Plagioclase		7.2	14.0	23.0	16.7	32.1	8.2	20.2	4.3
Biotite		21.5	33.7	4.7	7.8	19.8	22.9	14.4	17.0
Muscovite		4.9	11.2	0.6	11.7	7.6	20.2	14.9	9.1
Cordierite		11.0	4.5	9.4	—	—	—	3.1	0.7
Andalusite		—	0.1	0.6	0.6	—	—	—	—
Sillimanite		2.4	—	—	—	—	3.8	0.2	11.5
Opaques*		2.0	—	—	0.3	1.5	1.4	0.4	0.1
Others		1.0	0.9	0.1	2.4	0.5	4.4	0.5	1.7
Total		100.0	100.0	100.0	100.1	100.0	100.0	100.1	99.9

* Mainly graphite.

No.	1	2	3	4	5	6	7	8
Specimen No.	67122202	68122004	68122005	70112201	68032908	69121504	68050202	68050203

○ Quartz-plagioclase-biotite

Opaques, zircon and apatite are usually present in small amounts.

Summing up the mineralogical variations in pelitic and psammitic rocks, the variation diagram shown as Fig. 12 can be presented.

Zone I probably corresponds to the cordierite zone, Zone IIa to the first sil-

limanite zone and Zone IIb to the second sillimanite zone in the Komagane area respectively (HAYAMA, 1960, 1964a).

Modal compositions of several rocks are shown in Table 7.

D) Petrography

(1) Zone I

a) Pelitic and psammitic rocks

○ Hornfels (Specimen No. 71032603)

Mineral assemblage: Quartz-potash feldspar-plagioclase-biotite-muscovite

Very fine-grained. Quartz and feldspars form mosaic, and micas show preferred orientation. Plagioclase is polysynthetically twinned and weakly zoned around An 25. Myrmekite is developed inside the plagioclase which contacts with potash feldspar. Biotite is elongated flakes, and pleochroic with X=yellow, Y=Z=reddish brown. Muscovite is larger than other minerals and poikiloblastic.

○ Hornfels (Specimen No. 71032708)

Mineral assemblage: Quartz-plagioclase-biotite-muscovite-cordierite-andalusite

Tourmaline (abundant), graphite, ores and apatite are accessories.

Mica shows preferred orientation. Muscovite is porphyroblastic and in parallel intergrowth with biotite. Biotite is pleochroic with X=pale yellow, Y=Z=red brown. Andalusite is replaced by muscovite from the periphery. Cordierite shows sieve structure. Tourmaline is zoned with greyish brown core and yellowish brown rim.

○ Hornfels (Specimen No. 71032608)

Mineral assemblage: Quartz-plagioclase-biotite-muscovite-garnet

Dusty graphite and apatite are present as accessories.

Very fine-grained. Quartz forms mosaic, and biotite and muscovite are in parallel intergrowth and show preferred orientation. Plagioclase is granular grains, and of composition An22. Biotite is tiny scaly flakes. It is pleochroic with X=pale yellow, Y=Z=brown, and has $\gamma=1.632$. Garnet includes fine dusty materials and attains 0.3 mm. in diameter. Index of refraction $n=1.814$.

○ Hornfels (Specimen No. 71032604)

Mineral assemblage: Quartz-potash feldspar-plagioclase-biotite-muscovite-cordierite

Tourmaline, graphite, apatite, and iron ores are common accessories.

Derived from siliceous sandstone. Mica shows preferred orientation and other minerals form mosaic. Quartz is larger than other minerals in size. Both potash

feldspar and plagioclase are granular grains. Muscovite is long flakes. Biotite is tiny scaly flakes and pleochroic with X=nearly colourless, Y=Z=reddish brown. Cordierite is poikiloblastic and includes mica flakes.

○ Hornfels (Specimen No. 71081906)

Mineral assemblage: Quartz-plagioclase-biotite-muscovite

Tourmaline, apatite and carbonaceous matter are accessories. Besides these dust graphite is present.

Derived from shale. Very fine-grained. Quartz and feldspar form mosaic, and micas show preferred orientation, giving to the host rock schistosity. Plagioclase is small in amount and granular grains. Both biotite and muscovite are tiny scaly flakes. Biotite is pleochroic with X=very pale yellow, Y=Z=brown with reddish tint.

b) Siliceous rocks

○ Hornfels (Specimen No. 71032706)

Mineral assemblage: Quartz-plagioclase-biotite-muscovite-garnet

Tourmaline, apatite, zircon and ores are accessories.

Quartz is interlocked with suture-line each other. Mica shows parallel arrangement. Biotite is pleochroic with X=golden yellow, Y=Z=light brown. Garnet is xenomorphic and attains to 0.3 mm. in diameter.

○ Hornfels (Specimen No. 71032702)

Mineral assemblage: Quartz-muscovite

Ores and graphite are common accessories.

Very fine-grained rock. Original fine laminae are preserved. Quartz is elongated grains and interlocked each other with suture-line. Muscovite is frequently porphyroblastic and shows preferred orientation.

○ Hornfels (Specimen No. 74032504)

Mineral assemblage: Quartz-potash feldspar-muscovite

Graphite and ores are accessories.

Muscovite is very small elongated flakes and shows parallel arrangement. Quartz and potash feldspar form mosaic with zigzag outline.

(2) Zone IIa

a) Pelitic and psammitic rocks

○ Mica schist (Specimen No. 70092102)

Mineral assemblage: Quartz-plagioclase-biotite-muscovite-sillimanite

Tourmaline, zircon, apatite and opaques are accessories.

Spots, made of aggregate of biotite, muscovite and sillimanite, are sporadically distributed. These are the exactly equivalent to the porphyroblastic aggregate described by KOIDE (1958) in the Dando area. Both biotite and muscovite are partly replaced by fibrous sillimanite.

○ Mica schist (Specimen No. 70092103)

Derived from the alternation of sandstone and highly aluminous pelite, as shown in Fig. 10. Original sandstone part is now composed mainly of quartz, plagioclase, biotite, muscovite and sillimanite. Quartz and feldspar form mosaic, and micas show preferred orientation. Highly aluminous part is characterized by the presence of porphyroblastic andalusite. This part is composed mainly of quartz, plagioclase, biotite, muscovite, andalusite and sillimanite. Sillimanite, as fibrous felt, occurs as replaced parts of both biotite and muscovite. Porphyroblastic andalusite is surrounded by muscovite, but seems to have no genetical relations to sillimanite.

○ Mica schist (Specimen No. 67122202)

Mineral assemblage: Quartz-potash feldspar-plagioclase-biotite-muscovite-cordierite-sillimanite

Graphite, ore, tourmaline, apatite and zircon are accessories.

Derived from shale. Micas show preferred orientation and give the rock schistosity. Fibrous sillimanite replaces part of the biotite. It is also developed in muscovite flakes. Muscovite is usually in parallel intergrowth with biotite., but larger crosscutting ones are also present. Cordierite is almost always replaced by sericitic mica and/or pinitite. Potash feldspar shows fine streak-like perthite structure. Plagioclase is of compositions An15-25. Biotite occurs as slender flakes and is pleochroic with X=pale yellow, Y=Z=reddish brown. It has $\gamma=1.636$.

○ Gneiss (Specimen No. 68122004)

Mineral assemblage: Quartz-potash feldspar-plagioclase-biotite-muscovite-cordierite

Graphite, ore, zircon and apatite are common accessories.

Derived from shale. Banded with black biotitic seam and white quartzo-feldspathic seam. Micas show preferred orientation, and other minerals form equigranular mosaic. Potash feldspar is perthitic and shows moiré appearance. Plagioclase is tabular and weakly zoned around An28. Myrmekite is developed. Cordierite is almost altered to pinitite and/or sericitic mica. Muscovite occurs as two forms; in parallel growth with biotite and cross-cutting. Biotite is pleochroic with X=yellow, Y=Z=brown, and has $\gamma=1.640$.

○ Gneiss (Specimen No. 68122005) [Plate II-1]

Mineral assemblage: Quartz-potash feldspar-plagioclase-biotite-muscovite-

cordierite-andalusite

Ore, tourmaline, graphite, zircon and apatite are accessories.

Derived from psammitic rock. Rather massive rock. Potash feldspar shows streak-perthite structure. Plagioclase is xenomorphic and polysynthetically twinned (An₃₀). Cordierite is abundantly present and partly altered along crack, and it includes granular grains of quartz. Biotite is tiny scaly flakes and shows parallel arrangement. It is pleochroic with X=nearly colourless, Y=Z=brown, and has $\gamma=1.645$. Muscovite is small in amount, and in parallel intergrowth with biotite. Andalusite is irregular-shaped grains, sometimes associated with ore and/or biotite.

○ Gneiss (Specimen No. 74032207) [Plate II-2]

Mineral assemblage: Quartz-potash feldspar-plagioclase-biotite-cordierite-andalusite-sillimanite

Iron ores, apatite and graphite are accessories.

This rock is characterized by the transition of andalusite to sillimanite. Porphyroblastic andalusite is replaced by sillimanite from the periphery and spottedly. Andalusite is poikiloblastic including other minerals, such as biotite flakes and quartz. Sillimanite, replaced andalusite, is large prismatic. Fibrous sillimanite is also found, crowded in the cordierite crystals. It is also produced through the decomposition of biotites. Potash feldspar is large in size, showing well developed cleavages parallel to (010). It contacts with cordierite, suggesting their stable association. Plagioclase is small in amount and has composition An₂₄. Biotite is pleochroic with X=pale yellow, Y=Z=reddish brown, and has $\gamma=1.649$. It shows remarkable parallel orientation.

b) Siliceous rocks

○ Quartz schist (Specimen No. 70091901)

Mineral assemblage: Quartz-plagioclase-biotite-muscovite-garnet

Apatite, ore and zircon are accessories.

Derived from chert. Quartz is interlocked each other with suture-line. Plagioclase is xenomorphic and dirty. Both biotite and muscovite are small flakes and usually included in quartz crystal. Garnet is also small in diameter.

○ Quartz schist (Specimen No. 73030608)

Mineral assemblage: Quartz-potash feldspar-plagioclase-biotite-muscovite

Ore, zircon and apatite are accessories.

Derived from highly siliceous sandstone. Although it shows remarkable schistosity to the naked eye, under the microscope, it exhibits granular mosaic texture. Plagioclase is xenomorphic and weakly zoned. Potash feldspar is granular grains, and shows faint moiré appearance. Muscovite is irregular-shaped flakes.

Biotite is small in amount and tiny scaly flakes.

(3) Zone IIb

a) Pelitic and psammitic rocks

○ Gneiss (Specimen No. 68050202) [Plate II-3]

Mineral assemblage: Quartz-potash feldspar-plagioclase-biotite-muscovite-cordierite-sillimanite

Graphite, ores, apatite and zircon are accessories.

Banded in several millimetres in scale with biotitic black layer and quartzose white layer. Sillimanite occurs as felty aggregate of fibrolite. Trains of needle sillimanite cut the foliation of muscovite. Cordierite is altered to pinite and/or sericitic mica.

○ Gneiss (Specimen No. 70092003) [Plate II-4]

Mineral assemblage: Quartz-plagioclase-biotite-garnet-cordierite-muscovite

Ores, zircon and apatite are common accessories.

Derived from psammitic rock. Micas show parallel arrangement, and other minerals form mosaic. Plagioclase is irregular-shaped grains and polysynthetically twinned. It is of compositions An₂₅₋₃₂. Cordierite is granular grains and associated with both garnet and biotite. Garnet occurs as two fashions; aggregate of fine-grained crystals and larger discrete grains. The latter attain to 0.8 mm. in diameter. Biotite is elongated flakes and pleochroic with X=pale yellow, Y=Z=brown. Muscovite is small in amount and in parallel intergrowth with biotite.

○ Gneiss (Specimen No. 70082502)

Mineral assemblage: Quartz-plagioclase-biotite-muscovite-cordierite

Graphite, ores, apatite, zircon occur as accessories.

Of pelitic rock origin. Banded in millimetres scale with biotitic black layer and felsic white layer. Under the microscope, micas show strong preferred orientation, and other minerals form granular mosaic. Plagioclase is xenomorphic and polysynthetically twinned after albite-law. It is zoned weakly around An₃₀. Cordierite is granular grains and shows sieve structure. Biotite and muscovite are in parallel intergrowth and show parallel arrangement. Biotite is pleochroic with X=very pale yellow, Y=Z=brown and has index of refraction $\gamma=1.640$.

○ Gneiss (Specimen No. 69121503)

Mineral assemblage: Quartz-potash feldspar-plagioclase-biotite-muscovite-sillimanite

Iron ore, sphene, zircon and apatite are accessories.

Derived from pelitic rock. Felsic part shows granitic texture, and mica flakes

are in preferred orientation. Potash feldspar is small in quantity and granular grains. Plagioclase is hypidiomorphic tabular and polysynthetically twinned. It shows weak zoning (An₃₂₋₃₀). Biotite is elongated flakes. It is sometimes decomposed to sillimanite plus sphene from the periphery. It is pleochroic with X=pale yellow, Y=Z=deep brown with reddish tint. Muscovite is usually elongated flakes, intergrown with biotite. Sometimes large porphyroblastic, cross-cutting muscovites are found. Sillimanite occurs always as replaced the biotite, and it is fibrous to felty.

b) Siliceous rocks

○ Quartz gneiss (Specimen No. 68032710)

Mineral assemblage: Quartz-plagioclase-biotite

Opaque minerals, zircon and apatite are accessory minerals.

Derived from chert. Quartz is interlocked each other with suture-line and shows strong undulatory extinction. Plagioclase is irregular-shaped grains. Biotite is small well-shaped flakes, and pleochroic with X=colourless, Y=Z=yellow brown. It is always included in quartz.

○ Quartz gneiss (Specimen No. 68032709)

Mineral assemblage: Quartz-potash feldspar-plagioclase-muscovite-garnet

Opagues and apatite are accessories.

Both potash feldspar and plagioclase are fine-grained and irregular-shaped. They occasionally alter to sericitic mica. Muscovite and garnet are very small in amounts.

○ Quartz gneiss (Specimen No. 68032915)

Mineral assemblage: Quartz-plagioclase-biotite-muscovite-garnet

Opaque minerals are common accessories.

Derived from chert. Quartz is interlocked each other with suture-line and includes small crystals of other minerals. Plagioclase is xenomorphic and twinned. Biotite is small flakes and pleochroic with X=colourless, Y=Z=light brown. Muscovite is well-shaped flakes. Garnet is hypidiomorphic and 0.2 to 0.5 mm. in diametre.

○ Quartzite (Specimen No. 68032215b)

Mineral assemblage: Quartz-potash feldspar-plagioclase-biotite-muscovite

Derived from chert. Quartz is interlocked each other with suture-line and shows strong undulatory extinction. Both plagioclase and potash feldspar are small in size and dirty. Biotite is well-shaped flakes and is pleochroic with X=pale yellow, Y=Z=yellow brown. Muscovite is small in amount and tiny scaly flakes.

○ Quartzite (Specimen No. 68032210)

Mineral assemblage: Quartz-plagioclase-biotite-muscovite

Opaque minerals and zircon are common accessories.

Derived from chert. Petrographically it is almost the same as the above specimen except that potash feldspar is absent.

○ Quartzite (Specimen No. 67082501)

Mineral assemblage: Quartz-potash feldspar-plagioclase-muscovite

Derived from chert. Under the microscope, it shows mosaic texture. Quartz is granular grains. Potash feldspar is also granular and shows clear quadrille structure. Plagioclase is xenomorphic and is of composition An₁₅. Muscovite is elongated flakes.

○ Quartzite (Specimen No. 67073008)

Mineral assemblage: Quartz-potash feldspar-plagioclase-biotite

Derived from chert. Quartz includes small flakes of biotite. Potash feldspar is irregular-shaped grains, and shows faint moiré appearance. Plagioclase is small in size and polysynthetically twinned (An₈). Biotite is small irregular-shaped flakes, and has pleochroism of X=colourless, Y=Z=pale brown.

3. Metamorphic rocks derived from basic igneous rocks

These rocks are described in detail in the previous papers (KUTSUKAKE, 1970, 1975a), except for the metamorphosed basalt. Here, the essential points will be reproduced.

A) Original rocks

Their original rocks seem to be doleritic intrusive rocks of highly aluminous tholeiitic or calc-alkalic nature. They have probably intruded into the sedimentary rocks, now the Ryôke metamorphic rocks, before or in the early stage of the Ryôke regional metamorphism as dykes and/or sheet-like masses.

B) Chemical compositions

The rocks are rich in alumina and potash, but poor in magnesia. Metasomatic addition of potash and subtraction of some lime and magnesia can be safely assumed.

C) Mineralogical compositions

The main rock type is composed mainly of plagioclase, quartz, hornblende and biotite, sometimes with cummingtonite and potash feldspar. Ilmenite, pyrrhotite and chalcopyrite are main opaque minerals. Apatite, zircon and sphene are common accessories.

D) Petrography

The main rock type is fine-grained, dark greenish and massive rock. Under the microscope, it usually shows recrystallized granular texture, as seen in hornfels. But, sometimes it preserves original ophitic to subophitic texture, suggesting its doleritic original rock. The blastoporphyritic plagioclase retains the high-temperature optics of original igneous rock, even after the amphibolite-facies metamorphism and metasomatism.

Petrography of a metamorphosed basalt (Specimen No. 71081803)

As above described, small lens (about 3 m. thick) of basalt is intercalated in sedimentary rocks of Zone IIb. The rock is now amphibolite. It is dark greenish and gneissose rock. It is slightly banded with hornblendic dark layers and feldspathic white layers. Under the microscope, plagioclase forms granular mosaic and hornblende shows lattice orientation. It is composed mainly of plagioclase and hornblende, with small amount of quartz. As accessories, iron ore (mainly ilmenite), zircon, apatite and carbonate mineral are found. Plagioclase is granular grains and almost free from zoning. It is limited in narrow compositional range of An42-43. Hornblende is also granular grains. It is pleochroic with X=pale yellow, Y=brownish green, Z=brown with yellowish green tint. $c^{\wedge}Z=16.5^{\circ}$.

VIII. Mineralogy of Metamorphic Minerals

1. General statement

Main constituent minerals of the metamorphic rocks will be described in regard to their chemical and physical, optical among others, properties. Mutual relations between the minerals are also discussed mainly from the mineralogical points of view. Phase equilibria among them will be discussed in the later sections dealing with the metamorphic conditions.

2. Quartz

It is present in almost all the rock types. The grain-size generally increases with increasing grade of the metamorphism. Especially in Zone I, it is very fine-grained. In some rock types, such as quartz schist, it has an elongated form and shows preferred orientation.

3. Potash feldspar

It is granular grains and forms mosaic with other felsic minerals. Microcline structure can not be observed, but rarely faint moiré appearance is observable. Clear perthite structure is not observed but streak-like perthite (cleavage ?) is usually seen parallel to (010). Optical properties are summarized in Table 8. Optic axial angle seems to be larger with increasing metamorphism. This feature is opposite to the

Table 8. Optical properties of potash feldspars

Zone	Specimen No.	(-) $2V$	α	β	γ
IIa	68122004	60.5°			
	72090902	52°, 54°	1.519 ₈	1.524	1.526
	71081801B	51.5°	1.519	1.524	1.526
	71081805	62°			
IIb	68032913	74.5°			
	68032613	70°			
	68050202	60°			
	68050408	80.5°, 82°			
	68082203	76.5°, 77.5°			

Table 9. Triclinicity (Δ) of potash feldspars

Zone	Specimen No.	Δ
I	71032603	0.57 ₈
IIa	71081801B	0.16 ₈ (max.)
	68122004	0
IIb	68050202	0

fact that the optic angle of potash feldspar in the Ryôke metamorphic rocks in the Mitsue-mura area, Nara Prefecture, becomes smaller with increasing metamorphism (SUWA, 1961).

In the X-rayed diffraction pattern, the peaks of ($1\bar{3}1$) and (131) do separate for the materials of Zone I, but for those of Zones IIa and IIb, they do not separate, showing slight diffuseness (Fig. 13). Diffuseness is probably due to the mixtures of materials with variable angular distances. The triclinicity ($\Delta=12.5 [d(1\bar{3}1)-d(131)]$) defined by GOLDSMITH and LAVES (1954), is calculated for these potash feldspars with the results shown in Table 9.

HEIER (1957) suggested that potash feldspar acquires monoclinic symmetry at a grade slightly below the boundary between the granulite and amphibolite facies. SHIDÔ (1958) showed that the potash feldspars of the amphibolite facies metamorphic rocks in the central Abukuma plateau are orthoclase. Of the Ryôke metamorphic rocks, ONO (1969b) described as the potash feldspars are orthoclase. But, of the rocks in the Toyone-mura area, potash feldspars seem not always to be typical orthoclase having $\Delta=0$.

The compositions of some potash feldspars are estimated by means of the $20\bar{1}$ X-ray method by ORVILLE (1963). After dry homogenization of the feldspars at 1050°C for several hours, they are X-rayed by use of $\text{CuK}\alpha$ radiation at a scanning speed of 1°/4 min. with KBrO_3 as an internal standard. On a chart the angular

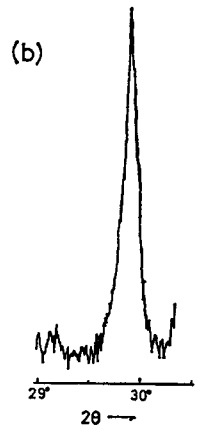
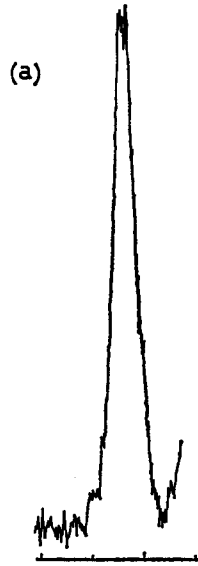


Fig. 13. 131 and $\bar{1}\bar{3}1$ of reflections in powder diffraction patterns of potash feldspars.

- (a) potash feldspar in gneiss (Specimen No. 71081801B) in Zone IIa.
- (b) potash feldspar in gneiss (Specimen No. 68050202) in Zone IIb.

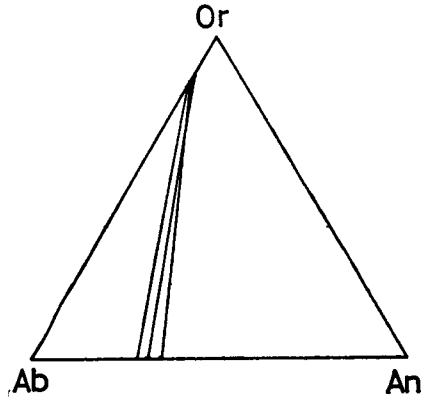


Fig. 14. Compositions of coexisting potash feldspar and plagioclase in pelitic metamorphic rocks.

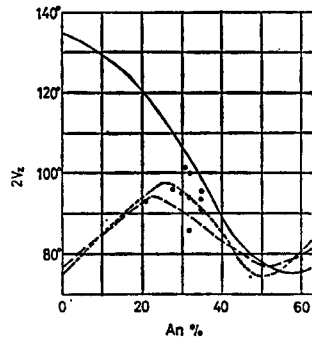


Fig. 15. Optic axial angles of plagioclases in pelitic and psammitic metamorphic rocks.

- : high-temperature form after SMITH (1958),
- - -: low-temperature form after SMITH (1958),
-: low-temperature form after VAN DER KAADEN (1951).

distance between $2\theta_{201}$ of potash feldspar and $2\theta_{101}$ of KBrO_3 is measured, therefrom the composition is estimated on the diagram by ORVILLE. The results are as follows;

Zone	Specimen No.	$\Delta 2\theta$	Comp.
IIa	72090902	0.85°	$\text{Or}_{86}\text{Ab}_{14}$
	71081801B	0.83°	$\text{Or}_{88}\text{Ab}_{12}$
IIb	68050202	0.84°	$\text{Or}_{87}\text{Ab}_{13}$

They are plotted with their associated plagioclases in the diagram of Or-Ab-An (Fig. 14).

4. Plagioclase

Compositions of the plagioclases are determined by the immersion method, after Tsuboi's (1923, 1968) diagrams. Most of the plagioclases in pelitic and psammitic metamorphic rocks fall in the range from basic oligoclase to acid andesine. Optic axial angle *versus* composition is shown in Fig. 15. Some of them do not

Table 10. $\Delta[2\theta(1\bar{3}1) - 2\theta(131)]$ of plagioclases

Zone	Specimen No.	$2\theta(1\bar{3}1)$	$2\theta(131)$	Δ
I	72032603	31.52°	29.90°	1.62°
	71032708	31.41° (broad)	29.94°	1.47°
IIa	68122004	31.49°	29.82°	1.67°
	70092102	31.15°	29.74°	1.41°
IIb	68050202	31.44°	29.75°	1.65°

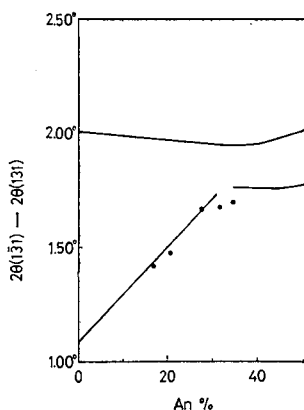


Fig. 16. Angular separations between the (131) and $(1\bar{3}1)$ reflections of plagioclases.

lay on the curves of plutonic (low-temperature) plagioclase, proposed by VAN DER KAADEN (1951) and SMITH (1958).

Triclinicity ($\Delta=2\theta(1\bar{3}1)-2\theta(131)$) defined by SMITH and YODER (1956) is measured for several plagioclases (Table 10). They are plotted in the diagram (Fig. 16). They shown typical "low-temperature form".

5. Muscovite

It is one of the commonest minerals in pelitic and psammitic metamorphic rocks through the three zones. It is usually slender flakes and frequently in parallel intergrowth with biotite. Sometimes porphyroblastic, cross-cutting ones are observed, this may be later development due to the granite contact, as suggested by ONO (1969b). In Zone IIb, it is decomposed to sillimanite from the periphery, suggesting the reaction; muscovite+quartz \rightarrow potash feldspar+sillimanite+water.

Chemical analysis of a specimen in the gneiss (Specimen No. 68050202) in Zone IIb was made, with the result shown in Table 11. Na/K ratio, i.e., paragonite to muscovite molecular ratio, is $0.229/1.459=0.157$. This muscovite includes 10.4 mol. per cent of phengite molecule.

Optical properties are summarized in Table 12. No contrasting features between the two zones can be recognized.

Table 11. Chemical composition of a muscovite

		Numbers of ions on the basis of 24(O, OH)	
SiO ₂	48.44	Si	6.411
TiO ₂	0.46	Al ^{IV}	1.589
Al ₂ O ₃	33.36	Al ^{VI}	3.615
Fe ₂ O ₃	1.22	Ti	0.046
FeO	1.40	Fe ⁺³	0.121
MnO	0.10	Fe ⁺²	0.155
MgO	1.20	Mn	0.011
CaO	0.17	Mg	0.134
Na ₂ O	0.89	Ca	0.024
K ₂ O	8.64	Na	0.229
H ₂ O(+)	4.37	K	1.459
H ₂ O(-)	0.60	OH	3.862
Total	100.85		

Anal. T. KUTSUKAKE

R.I. $\beta=1.594$, $\gamma=1.600$; $(-)2V=39^\circ$.

Basal spacings: $d_{002}=10.003\text{\AA}$, $d_{003}=3.332\text{\AA}$; 1M type.

Host rock: gneiss (Specimen No. 68050202) in Zone IIb.

The associated biotite is analyzed (Table 13, No. 2).

Table 12. Optical properties of muscovites

Zone	Specimen No.	β	γ	(-) $2V$
IIa	70092102	1.592	1.597	
	70092103	1.596	1.601	
	68122004	1.594	1.599	39.5°
	68122005	1.594	1.601	
	72090902			41°
	71081801B			31°
	68032908			30°
IIb	69121303			38°
	69121504		1.597	39°
	70082502		1.600	
	68050202	1.594	1.600	39°
	71121704		1.604	

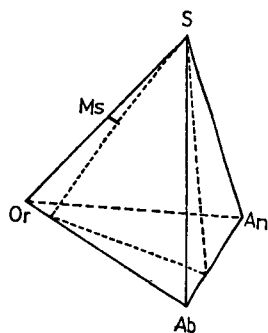


Fig. 17. Phase relations of coexisting sillimanite, muscovite, potash feldspar and plagioclase in gneiss (Specimen No. 68050202) in Zone IIb.

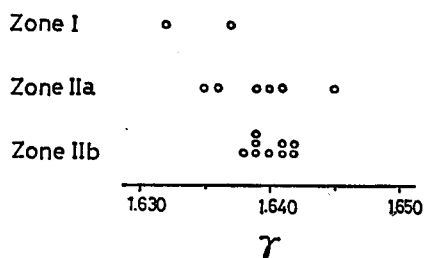


Fig. 18. Distribution of the refractive index γ of biotite in pelitic and psammitic metamorphic rocks.

Coexisting potash feldspar, plagioclase and muscovite in the gneiss (Specimen No. 68050202) of Zone IIb are plotted in the tetrahedron of sillimanite-orthoclase-albite-anorthite (Fig. 17). This situation of the diagram is very similar to that of the rocks above the sillimanite-potash feldspar isograd, Western Maine (EVANS and GUIDOTTI, 1966).

6. Biotite

It occurs abundantly in almost all the rock types. It is slender flakes and usually shows preferred orientation. Frequently it changes to sillimanite from the periphery through decolourization. In pelitic and psammitic metamorphic rocks, it usually shows brown to reddish brown colour along Z-axis. But, in siliceous rocks it is

yellowish brown to light brown in Z-axial colour.

Refractive index γ is plotted in terms of metamorphic zones. Apparently index of refraction slightly increases with increasing metamorphism (Fig. 18).

Basal spacing of some specimens are shown below;

Zone	Specimen No.	d_{001}
IIb	68050202	10.070Å
	68050203	10.094Å
	68050205	10.117Å

Chemical analyses for five specimens are carried out with the results shown in Table 13. In the diagram of Fe^{3+} - Fe^{2+} -Mg, the analyses are plotted near the Fe^{2+} -Mg side (Fig. 19), thus the low oxygen fugacity during their formation is suggested (WONES and EUGSTER, 1965).

Composition of biotites in metamorphic rocks has been discussed in terms of bulk composition and metamorphic grade of host rock by many authors (e.g., ENGEL and ENGEL, 1960; HAYAMA, 1959b; WENK, 1970). It has been shown that Fe in biotite increases in general with increasing metamorphic grade, whereas Ti, Mg and Al decrease. In Japan too, chemical composition of biotites in metamorphic rocks has been discussed from the above mentioned points of view, especially for the Ryôke metamorphic rocks (MIYASHIRO, 1956; ÔKI, 1961b; HAYAMA, 1964a; ONO, 1969b; HONMA, 1974). The chemical analyses of biotites, so far reported, in pelitic and psammitic metamorphic rocks in the Ryôke zone of the Chûbu district (TSUBOI, 1938; MIYASHIRO, 1956; ÔKI, 1961b; HAYAMA, 1964a; SHIBATA, 1968; ONO, 1969b, 1975a, b) are compiled herein. They are plotted in three diagrams in terms of zonal classification (Figs. 20; 21-a, -b).

Slight increase of Al with increasing metamorphic grade can be obtained from

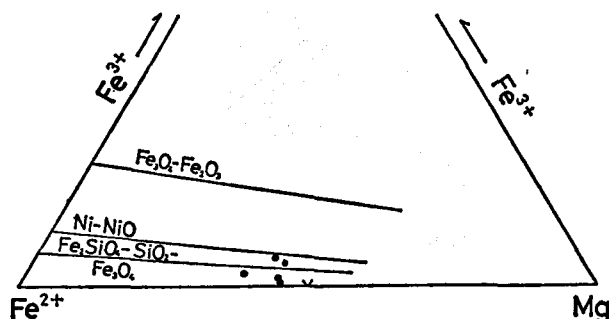


Fig. 19. The Fe^{3+} - Fe^{2+} -Mg (cation per cent) diagram for biotites. Solid lines represent compositions of "buffered" biotites in the ternary system $\text{KFe}_3^{3+}\text{AlSi}_3\text{O}_{12}\text{H}_{-1}$ - $\text{KFe}_3^{2+}\text{AlSi}_3\text{O}_{10}$ - $\text{KMg}_3\text{AlSi}_3\text{O}_{10}(\text{OH})$ by WONES and EUGSTER (1965).

Table 13. Chemical compositions of biotites

	1	2	3	4	5
SiO ₂	34.01	33.86	35.38	33.22	33.13
TiO ₂	1.67	2.03	2.15	2.55	1.71
Al ₂ O ₃	23.28	20.80	18.56	20.80	20.01
Fe ₂ O ₃	1.79	0.88	2.30	0.47	0.17
FeO	17.77	18.47	19.29	19.68	20.59
MnO	0.28	0.47	0.17	0.25	1.20
MgO	8.36	8.55	8.45	9.02	9.47
CaO	0.00	0.02	0.00	0.00	0.36
Na ₂ O	0.29	0.24	0.40	0.32	0.54
K ₂ O	7.90	8.78	9.12	7.69	7.78
H ₂ O(+)	4.20	4.50	3.64	4.58	3.98
H ₂ O(-)	0.42	0.52	0.27	0.69	0.84
Total	99.97	99.12	99.73	99.27	99.78

Numbers of ions on the basis of 24(O, OH)

Si	5.083	5.007	5.430	5.096	5.100
Al ^{IV}	2.917	2.993	2.570	2.904	2.900
Al ^{VI}	1.183	0.631	0.787	0.858	0.732
Ti	0.188	0.226	0.248	0.294	0.198
Fe ⁺³	0.201	0.098	0.266	0.054	0.020
Fe ⁺²	2.221	2.929	2.476	2.525	2.651
Mn	0.035	0.058	0.022	0.032	0.156
Mg	1.862	1.844	1.933	2.043	2.173
Ca	0.000	0.000	0.000	0.000	0.059
Na	0.084	0.066	0.120	0.096	0.161
K	1.506	1.656	1.713	1.444	1.528
OH	4.120	4.441	3.726	4.684	4.070

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- No. 1: Biotite from gneiss (Specimen No. 72090903) in Zone IIa. The host rock is petrographically nearly the same as Specimen No. 68122005, described in pages 74-75. It is pleochroic with X=nearly colourless, Y=Z=brown, and has $\gamma=1.645$.
- No. 2: Biotite from gneiss (Specimen No. 68050202) in Zone IIb. Petrography of the host rock is given in page 76. The associated muscovite is analyzed (Table 11). It is pleochroic with X=pale yellow, Y=Z=red brown, and has $\gamma=1.639$.
- No. 3: Biotite from gneiss (Specimen No. 68050203) in Zone IIb. It is pleochroic with X=pale yellow, Y=Z=red brown, and has $\gamma=1.639$.
- No. 4: Biotite from quartz-potash feldspar-plagioclase-biotite-muscovite-sillimanite gneiss (Specimen No. 68050205) in Zone IIb. It is pleochroic with X=yellow, Y=Z=red brown, and has $\gamma=1.638$.
- No. 5: Biotite from gneiss (Specimen No. 70092003) in Zone IIb. Petrography of the host rock is given in page 76. The associated garnet and cordierite are analyzed (Table 14, No. 2; Table 15). It is pleochroic with X=pale yellow, Y=Z=brown, and has $\gamma=1.641$.

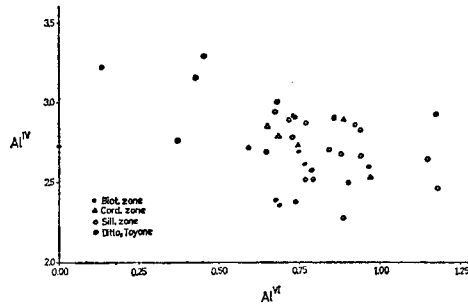


Fig. 20. Al^{IV} - Al^{VI} relations of biotites in pelitic and psammitic metamorphic rocks in the Ryôke zone of the Chûbu district.

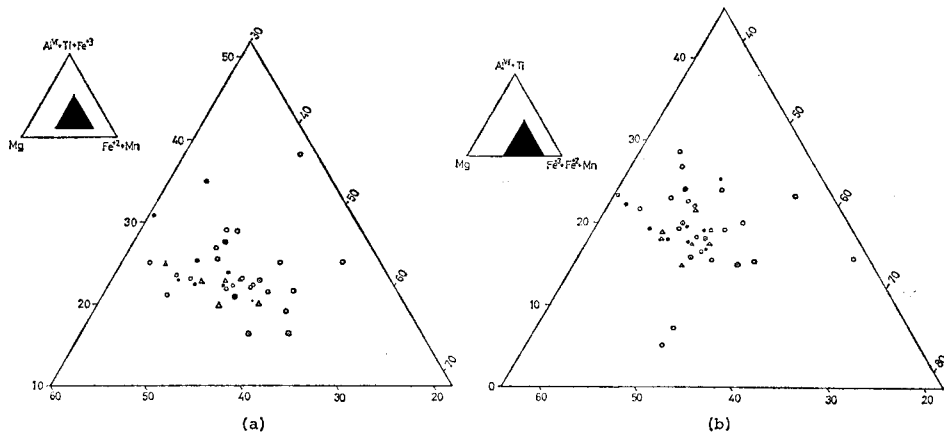


Fig. 21-a. $Al^{VI}+Ti+Fe^{+3}$ - Mg - $Fe^{+2}+Mn$ relations in six-coordinated cations in biotites,

-b. $Al^{VI}+Ti$ - Mg - $Fe^{+3}+Fe^{+2}+Mn$ relations in six-coordinated cations in biotites in pelitic and psammitic metamorphic rocks in the Ryôke zone of the Chûbu district.

the Fig. 20. Poverty of Al in the biotites in the biotite zone is conspicuous. In six-coordinated cations, general tendency of increasing of $Fe^{+2}+Mn$ with increasing metamorphic grade can be recognized (Fig. 21-a). However, any pronounced tendencies can be observed when Fe^{+3} is incorporated into Fe (Fig. 21-b). Therefore, it is sure that both Al and Fe^{+2} increase in biotites with increasing grade of the Ryôke regional metamorphism. This fact conflicts with the above mentioned general trend that Al decreases with increasing metamorphic grade. On the other hand, it is in accordance with the general trend in respect to the increase of Fe^{+2} .

7. Garnet

It occurs in highly manganese-rich pelitic and psammitic metamorphic rocks. In siliceous metamorphic rocks, such as metamorphosed chert, it is one of the common constituents.

It is small granular grains with diameter attaining to 0.5 mm, and frequently includes other minerals, such as quartz.

Two chemical analyses are made with the results shown in Table 14, with some physical properties. Both garnets have similar compositions, of about 3:1 of almandine to spessartine with some other end-members. Zoning in regard to Mg, Fe, Mn and Ca by electron-probe microanalyser scanning (Specimen No. 70092003) is shown in Fig. 22. No remarkable zoning for each ion can not be detected except for slight oscillatory zoning concomitant in regard to Fe and Mn.

Table 14. Chemical compositions and physical properties of garnets

		Numbers of ions on the basis of 24(O)	
	1	2	
SiO ₂	38.72	36.58	
TiO ₂	0.11	0.06	
Al ₂ O ₃	22.02	21.86	
Fe ₂ O ₃	0.00	2.29	
FeO	23.00	23.48	
MnO	12.23	11.66	
MgO	1.91	2.34	
CaO	0.98	0.87	
Na ₂ O	0.14	0.10	
K ₂ O	0.13	0.10	
H ₂ O(-)	0.04	0.11	
Total	99.28	99.44	
n	1.814	1.819	
a ₀	11.56Å	11.56Å	
- Mol. per cent end-members			
Almandine	57.4	57.9	
Andradite	0.7	2.8	
Grossular	2.4	—	
Pyrope	8.5	10.4	
Spessartine	30.9	29.1	

Anal. T. KUTSUKAKE

No. 1: Garnet from hornfels (Specimen No. 71032608) in zone I. Petrography of the host rock is given in page 72.

No. 2: Garnet from gneiss (Specimen No. 70092003) in zone IIb. Petrography of the host rock is given in page 76. The associated cordierite and biotite are analyzed (Table 15; Table 13, No. 5).

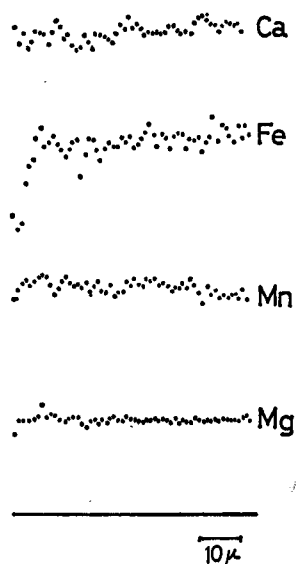


Fig. 22. Electron-probe microanalyser scanning of garnet in gneiss (Specimen No. 70092003) in Zone IIb.

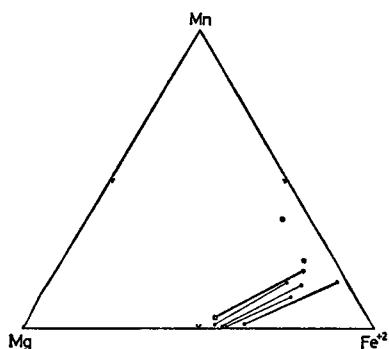


Fig. 23. Plots of coexisting garnet and biotite in Mn-Mg-Fe²⁺ diagram in pelitic and psammitic metamorphic rocks in the Ryôke zone of the Chûbu district.

(Open circle: garnet, Toyone,
Solid circle: garnet, other areas,
Open square: biotite, Toyone,
Solid square: biotite, other areas.

Coexistent garnet and biotite are plotted in the diagram of Fe²⁺-Mn-Mg (Fig. 23), the tie-line between them does not intersect each other. This fact suggests that the equilibrium may have well attained during the metamorphism (MIYASHIRO, 1953, 1956).

8. Cordierite

It is granular grains and sometimes shows sieve structure, including abundant small quartz crystals. It is rarely fresh but frequently replaced by epitaxial muscovite and/or pinitite completely or partly from the periphery. This is probably due to the retrogressive metamorphism or contact metamorphism by the granites.

Separated material is X-rayed and measured distortion index (d) is 0.27 (Specimen No. 70092003), which is the same value as that of the Komagane area (MIYASHIRO, 1957).

Optical properties are as follows;

Zone	Specimen No.	α	β	γ	(-) $2V$
IIa	71081805				74°
	74032207	1.543	1.550	1.556	78°
IIb	70092003	1.549	1.556	1.560	72°

Table 15. Chemical composition and physical properties of a cordierite

		Numbers of ions on the basis of 18 oxygens	
SiO ₂	48.08	Si	5.144
TiO ₂	0.37	Al ^{IV}	0.856
Al ₂ O ₃	30.25	Al ^{VI}	2.960
Fe ₂ O ₃	0.76	Ti	0.030
FeO	7.91	Fe ⁺³	0.062
MnO	0.24	Fe ⁺²	0.708
MgO	6.60	Mn	0.022
CaO	0.00	Mg	1.053
Na ₂ O	0.58	Ca	0.000
K ₂ O	0.02	Na	0.120
H ₂ O(+)	3.61	K	0.003
H ₂ O(-)	1.16		
Total	99.58	$\frac{\text{Fe}^{+2} + \text{Mn}}{\text{Fe}^{+2} + \text{Mn} + \text{Mg}} \times 100 = 40.9$	
Distortion index		$\alpha = 1.549$	
$\Delta = 0.27$		$\beta = 1.556$	
		$\gamma = 1.560$	
		$(-)\text{2V} = 72^\circ$	

Anal. T. KUTSUKAKE

Cordierite from gneiss (Specimen No. 70092003) in zone IIb.

Petrography of the host rock is given in page 76.

The associated garnet and biotite are analyzed (Table 14, No. 2; Table 13, No. 5).

Chemical composition of a specimen (No. 70092003) is shown in Table 15. This cordierite is rather rich in iron. Abnormally high water content is due to slight alteration to micaceous materials.

9. Andalusite and sillimanite

Andalusite usually occurs in pelitic metamorphic rocks of highly aluminous composition, but rarely in siliceous rocks, e.g., the rock (Specimen No. 70112201) which has SiO₂ 72.29 wt. per cent.

It is xenomorphic and frequently replaced by muscovite from the periphery. To the naked eye, it is pinkish in colour, but under the microscope, it shows pale yellowish colour. Optical properties of some andalusites are shown in Table 16.

In Zone IIa andalusite to sillimanite transition takes place, and the former is partly or completely replaced by the latter. But, as a rare case, they seem to have no genetical relations each other, even though they are coexistent in a rock, e.g.,

Table 16. Optical properties of andalusites

Zone	Specimen No.	α	β	γ	(-)2V
IIa	74032207	1.635	1.640	1.647	82°
	71081805				74°
	70092103	1.633	1.639	1.645	89°46' (calc.)
	70112201				83°

Specimen No. 70092103.

Sillimanite, replaced andalusite, is long prismatic, attaining to 5 cm in length. It is rarely made of single crystal, but usually composed of several individuals. It sometimes bears andalusite in its core as a relict. Other sillimanites are usually fibrous. In some rocks sworls and radial clusters of curving sillimanite fibers are conspicuous. Some sillimanites apparently formed late, replacing muscovite or, less usually, biotite in curving trains of fibers.

Optical properties of a sillimanite in the rock (Specimen No. 74032207) in Zone IIa are as follows; $\alpha=1.661$, $\beta=1.663$, $\gamma=1.681$; (+)2V=23°.

10. Hornblende and cummingtonite

These are common constituents of the metabasites. Mineralogy of hornblende and cummingtonite of the metabasites as well as those of the gabbros have been described in detail in the foregoing papers (KUTSUKAKE, 1974, 1975a). Here, the optical properties of the hornblende in a metamorphosed basalt (Specimen No. 71081803) in Zone IIb are presented;

$$\text{Refractive indices} \begin{cases} \alpha=1.657 \\ \beta=1.672 \\ \gamma=1.681 \end{cases} \quad \text{Pleochroism} \begin{cases} X=\text{pale yellowish brown} \\ Y=\text{dirty yellow brown} \\ Z=\text{yellow brown with greenish tint} \end{cases}$$

$$\text{Birefringence } \gamma-\alpha=0.024 \quad \text{Absorption } X < Y = Z$$

$$\text{Optic axial angle } (-)2V=78^\circ \quad \text{Dispersion } r > v, \text{ moderate}$$

$$\text{Optic orientation } c \wedge Z=16^\circ \text{ on } (010)$$

11. Tourmaline

It is usually present in pelitic and psammitic metamorphic rocks, but rarely in siliceous metamorphic rocks.

It is small crystals (~0.5 mm in diameter), and frequently zoned with deep brownish core and pale brownish to yellow-brownish rim.

12. Oxide and sulfide minerals

Polished specimens are examined by reflected light and opaque minerals are determined. In the sedimentogeneous metamorphic rocks, ilmenite is a common

Table 17. Oxide and sulfide minerals in sedimentogeneous metamorphic rocks in the Toyone-mura area

Zone	Specimen No.	ilmenite	pyrrhotite	chalcopyrite
I	71032603	—		+
	71032708		++	+
	71032608			
IIa	67122202	+	+	—(?)
	70092102	++	+	—
	70092103	—	—	
	68122004		—	
	68122005	+	++	—
	70112102	+	—	
	68032908		+	
	71081801B	+	—	—
IIb	71121703	+		
	70092003		—	
	69121504	+	—	—
	71121803	+		
	68050203		+	—

++: abundant, +: common, -: rare.

oxide mineral and pyrrhotite and chalcopyrite are usually observed as sulfides. Mineral assemblages of oxide and sulfide minerals are summarized in Table 17. In all the examined rocks, magnetite is absent.

13. Other minerals

Graphite. It occurs abundantly in pelitic metamorphic rocks through the zones. It is dusty and forms streaks in the rocks of Zone I. In Zones IIa and IIb, it grows larger in size and frequently associated with muscovite and/or sillimanite.

According to ONO (1972), the graphites in the Ryôke metamorphic rocks in the zones higher than the biotite zone are fully ordered, and amorphous carbonaceous matters are not detected.

Manganese minerals. At Hakuchô-yama in Tsugu-mura, manganese ore deposit is developed in the metamorphosed chert. The ore deposit must have been metamorphosed together with the surrounding country rocks at the time of the Ryôke regional metamorphism. From the deposit various manganese minerals, such as rhodonite, tephroite, manganophyllite and others, have been reported by YOSHIMURA (1967).

IX. Metamorphic Conditions

1. General statement

The nature of the Ryôke regional metamorphism has been discussed by several authors (MIYASHIRO, 1961; HAYAMA, 1964a; KATADA, 1967; ONO, 1969b). The metamorphism has been generally regarded to have taken place under the low-pressure and high-temperature condition, and the Ryôke zone is one of the famous metamorphic terrains of representative andalusite-sillimanite type facies series of MIYASHIRO (1961, 1973).

In this chapter, the physical conditions, especially P-T, of the metamorphism are enumerated from the viewpoints of mineralogical equilibria and metamorphic reactions. Also, other physical conditions revealed by mineralogical aspects will be discussed in some detail.

2. Mineral parageneses and metamorphic facies—with special reference to the concept of the K-feldspar-cordierite hornfels facies

Mineral parageneses in pelitic and psammitic metamorphic rocks in Zone IIb are shown in AKF diagram (Fig. 24). One of the characteristic mineral parageneses in these metamorphic rocks is the association of cordierite-K-feldspar. This is commonly observed in the rocks which belong to the cordierite zone and the more higher-grade zones of the Ryôke regional metamorphism. In this connection, ISHIOKA (1974) insisted that the Ryôke regional metamorphism should be called “the regional thermal metamorphism”, characterized by the association of cordierite and K-feldspar. This association is generally found in the hornfelses in the contact aureole.

WINKLER (1967) proposed a new metamorphic facies, the K-feldspar-cordierite hornfels facies, adopted to a series of contact metamorphic rocks, characterized by that association. And he divided it into two subfacies; lower-temperature “ortho-

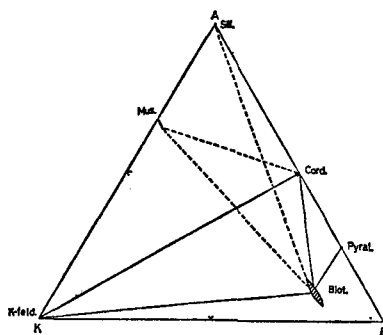


Fig. 24. AKF diagram for the rocks of Zone IIb.

amphibole subfacies” and higher-temperature “orthopyroxene subfacies”. The boundary between the two subfacies should be defined by such a reaction as: anthophyllite \rightarrow 7enstatite + quartz + water (GREENWOOD, 1963). This facies corresponds to the pyroxene hornfels facies of TURNER (1958). Formerly TURNER (1958) insisted that cordierite compatible with K-feldspar and/or sillimanite is typical to the pyroxene hornfels facies. However, in the Ryôke regional metamorphism cordierite-K-feldspar association is already stable even below the sillimanite zone. Moreover, in both the cordierite and sillimanite zones, cordierite and K-feldspar are characteristically compatible with muscovite. The presence of muscovite implies that those rocks do not belong to the pyroxene hornfels facies as well as to the K-feldspar-cordierite hornfels facies. Also, even in the highest-grade part of the Ryôke metamorphic terrain, no metamorphic orthopyroxene*, the most typical mineral to the pyroxene hornfels facies, has been found to occur in both the basic and pelitic rocks (HAYAMA, 1964b; KUTSUKAKE, 1974, 1975a). Therefore, it may be surely concluded that the pyroxene hornfels facies condition has not prevailed during the Ryôke regional metamorphism, and the metamorphism does not belong to the K-feldspar-cordierite hornfels facies, but to TURNER’s hornblende hornfels facies which corresponds to the lower-pressure part of the amphibolite facies in general concept. Thus the K-feldspar-cordierite association does not always show the K-feldspar-cordierite hornfels facies condition.

3. Andalusite to sillimanite transition

As already described, in Zone IIa andalusite is replaced by sillimanite partly or completely. Therefore, in this zone the transition of andalusite to sillimanite has taken place with the progression of the metamorphism. This transition has been used to mark the first sillimanite isograd in several metamorphic terrains. For the Ryôke zone, HAYAMA (1960) was the first to define the first sillimanite isograd by this transition.

However, the transition curve between andalusite and sillimanite is not settled so far, in spite of numerous experimental studies carried out in many laboratories. In Fig. 25, three transition curves are shown (FYFE and TURNER, 1966; RICHARDSON *et al.*, 1968; ALTHAUS, 1969). In any case the temperature at the first sillimanite isograd is fairly variable.

4. Muscovite breakdown

As already described, in the highest-grade part of this area, muscovite is partly replaced by sillimanite, and the assemblage: sillimanite-orthoclase-muscovite-quartz is frequently observed. The initiation of the breakdown of muscovite has been

* However, orthopyroxenes, ferrohypersthene to ferrosilite, have been reported from the highly ferriferous metabasic rocks as eulysite-like rocks (YOSHIZAWA, 1952).

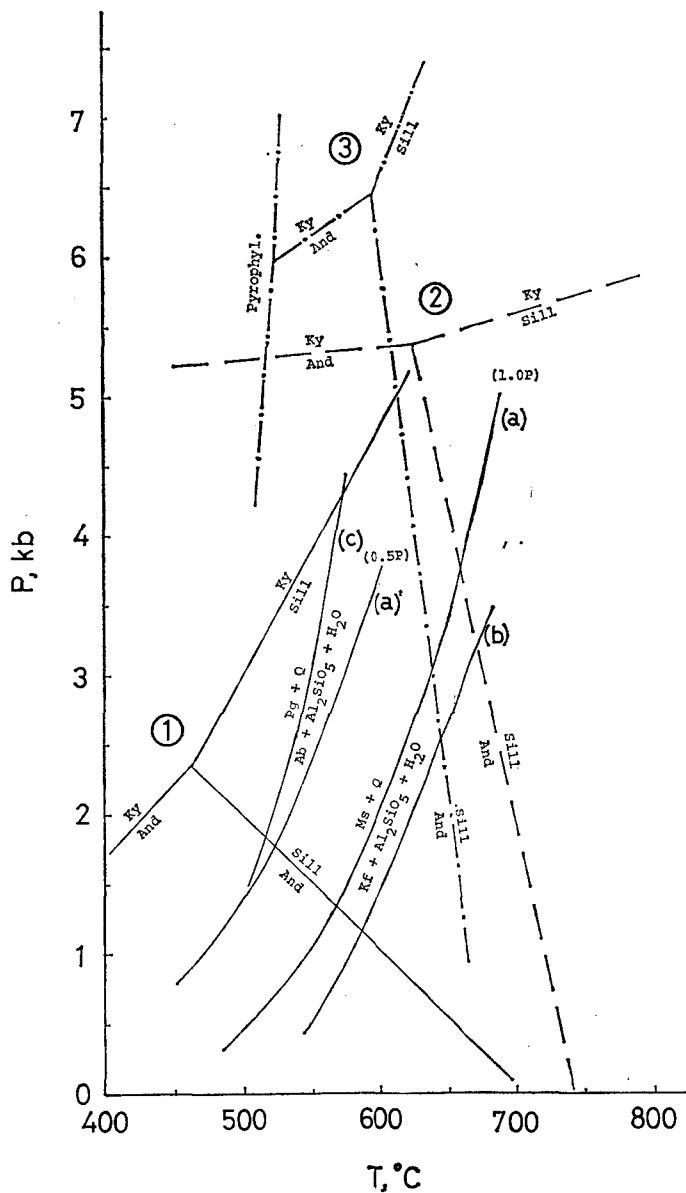


Fig. 25. Phase diagram showing stability fields of the polymorphs of Al₂SiO₆.

① FYFE and TURNER (1966)

② RICHARDSON *et al.* (1968)

③ ALTHAUS (1967)

Equilibrium curves for breakdown of micas.

(a) muscovite + quartz, at $P_{H_2O} = P_{total}$, after EVANS (1965)

(a') ditto, at $P_{H_2O} = 0.5P_{total}$, after EVANS (*op. cit.*)

(b) ditto, at $P_{H_2O} = P_{total}$, after ALTHAUS *et al.* (1970)

(c) paragonite + quartz, at $P_{H_2O} = P_{total}$, after CHATTERJEE (1972)

used to mark the second sillimanite isograd in several metamorphic terrains.

In contact metamorphism, excluding examples in which the mica is described as secondary, no cases of coexisting orthoclase- Al_2SiO_5 -muscovite (+plagioclase and quartz) have been found (EVANS and GUIDOTTI, 1966). In regional metamorphism we have now several recorded occurrences of the assemblage; sillimanite-orthoclase-muscovite-quartz (e.g., SNYDER, 1961, 1964; FISHER, 1941, 1942; FOWLER-BILLINGS, 1949; WELLS *et al.*, 1964). And also there exist many other examples from elsewhere muscovite is not reported alongside sillimanite and orthoclase (e.g., BARKER, 1961, 1962; LUNDGREN, 1966; CHAPMAN, 1952; HEALD, 1950 all in Appalachian; SCHREYER *et al.*, 1964; FRANCIS, 1956; MISCH, 1964 and BINNS, 1964). In Japan too, this assemblage has been reported from the Gosaisyo-Takanuki district, central Abukuma plateau (MIYASHIRO, 1958) and from the Ryôke metamorphic terrain in the Komagane area (HAYAMA, 1964a).

Gibbs Phase Rule says that the assemblage: sillimanite-orthoclase-muscovite-quartz may possess a variance of two. The wide spread occurrence of this assemblage in these metamorphic rocks similarly indicates a variance of not less than two. However, when the equilibrium phase diagram is considered in the light of the probable variability in rock composition, it appears that for all practical purposes, that the assemblage be univariant in P and T. The conflict may be resolved if normally independent intensive variable other than P and T were subject to control. The variance could be well $P_{\text{H}_2\text{O}}$, which rising due to the combination of rapid dehydration and low permeability is buffered by the above assemblage and controlled by local value of P and T.

The reaction curve: muscovite + quartz \longrightarrow Al_2SiO_5 + K-feldspar + water, has been determined experimentally by SEGNI and KENNEDY (1961) and ALTHAUS *et al.* (1970) and theoretically by EVANS (1965). The curve by each author is shown in Fig. 25. The lower limit of this reaction will depend on the value of $P_{\text{total}} - P_{\text{H}_2\text{O}}$. The depression of the equilibrium curve under unequal water and load pressures is as follows; when $P_{\text{H}_2\text{O}} = 0.5P_{\text{total}}$, the depression of the curve amounts to about 65 degrees in temperature, as shown in the diagram (EVANS, 1965). Also, at 6 kilobars total pressure and 1 kilobars water pressure, for example, would be, according to V_{solid} , about 200°C (i.e., approximately 525°C vs. 720°C) (EVANS and GUIDOTTI, 1966). Although the pressure of water-vapour during the metamorphism is very difficult to estimate, it must have been lower than the total pressure. Therefore, this reaction would have occurred at lower temperature side than the curves shown in the diagram.

Muscovite, incorporating paragonite molecule as solid solution, is also depressed its breakdown temperature. The reaction curve of paragonite plus quartz when $P_{\text{H}_2\text{O}} = P_{\text{total}}$ is also shown in Fig. 25 (CHATTERJEE, 1972). As already shown, the paragonite solid solution in the muscovite (Specimen No. 68050202, Table 11) in

Zone IIb is calculated as follows; $\text{Na/K} = 0.229/1.459 = 0.157$, which is nearly the same value as that of the Na/K ratio ($13/87 = 0.149$) of the coexisting K-feldspar. Therefore, in this case, the participant of albite molecule in the coexisting plagioclase to this reaction is not necessary to be taken into account. Thus, the reaction; muscovite+quartz+albite in plag. \rightarrow orthoclase+sillimanite+water, usually supposed for this kind of metamorphic reaction (EVANS and GUIDOTTI, 1966) is not required. And the univariant nature of this reaction can be safely assumed. But, the exact reaction curve can not be drawn on the diagram, for lack of the experimental and theoretical data for variable Na/K ratios as well as the informations of the pressure of water-vapour.

5. Garnet-cordierite-biotite equilibria

The rocks with the above assemblage are rarely found in the Ryôke metamorphic terrain. The analysis of the equilibrium relations of the three coexisting minerals in the Ryôke metamorphic rocks has also been made by ONO (1969b) in the Takatô area, north to the present area.

CHINNER (1962) suggested that with increasing of pressure of metamorphism, the triangle of cordierite-garnet-biotite in AFM-diagram deviates toward M-corner. The three minerals of a rock (Specimen No. 70092003) in Zone IIb are plotted in the diagrams (Fig. 26a, b), in comparison with the typical contact metamorphic rock, Isabella hornfels in Sierra Nevada Batholith (BEST and WEISS, 1964), and also to the Ryôke metamorphic rock in the Takatô area (ONO, 1969b). Differences between the situations of that of the Toyone and of the others can not be detected.



Fig. 26. Coexisting garnet, cordierite and biotite, plotted in
 (a) Al_2O_3 - $\text{FeO} + \text{MnO}$ - MgO diagram,
 (b) Al_2O_3 - FeO - MgO diagram.

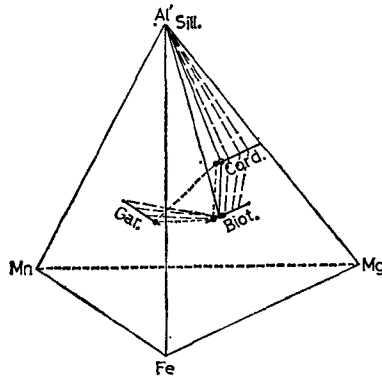


Fig. 27. Al'-Fe-Mg-Mn tetrahedron.

$$\begin{cases} \text{Al}' (\text{biotite}) = \text{Al} - (\text{K} + \text{Na} + \text{Ca}) \\ \text{Al}' (\text{cordierite}) = \text{Al} - 2 (\text{Mn} + \text{Ca}) \\ \text{Al}' (\text{garnet}) = \text{Al} - 2/3 (\text{Mn} + \text{Ca}) \end{cases}$$

Solid circle: mineral, analyzed.
Open circle: mineral, estimated.

Partition of Mg and Fe^{+2} between coexisting garnet and cordierite has been used as a geobarometer (OKURSCH, 1971; CURRIE, 1971). In the hypothetical diagram proposed by OKURSCH (1971, Fig. 6), the equilibrated pressure ($P_{\text{total}} = P_{\text{H}_2\text{O}}$), at 765°C, of the above mentioned rock can be read as corresponding to about 5 kilobars. Although the temperature of 765°C seems too high for the Ryôke regional metamorphism, pressure does not so reduced if temperature is lower by about 100°C. This pressure value must to be too high for the Ryôke regional metamorphism (TURNER, 1968). OKURSCH's diagram is not quantitatively valid, but qualitatively may be useful, as the Ryôke metamorphic rocks are plotted in the diagram between the typical contact metamorphic rocks and the higher-grade granulite facies metamorphic rocks as regard to pressure. The pressure during the Ryôke regional metamorphism would be slightly higher than that of the contact metamorphism.

Probable equilibrium relations of garnet, cordierite and biotite are shown in Fig. 27, in regard to those of Zone IIb, where sillimanite is also compatible.

6. Petrogenetic grid

The phase relations relevant to the understanding of the mineral parageneses and metamorphic reactions in the rocks of the present subject are summarized in Fig. 28.

The triple point of Al_2SiO_5 -polymorphs is cited from FYFE and TURNER (1966). The muscovite breakdown curve at $P_{\text{total}} = P_{\text{H}_2\text{O}}$ is taken from EVANS (1965). Other reaction curves for Mg-end members are from SCHREYER and SEIFERT (1969).

In this context, in estimating P-T condition during metamorphism by comparing natural mineral assemblages with experimental data, one must consider the greater complexity of natural reactions which involve components not present in laboratory studies. Moreover, laboratory studies are usually run at $P_{total} = P_{H_2O}$ but this may

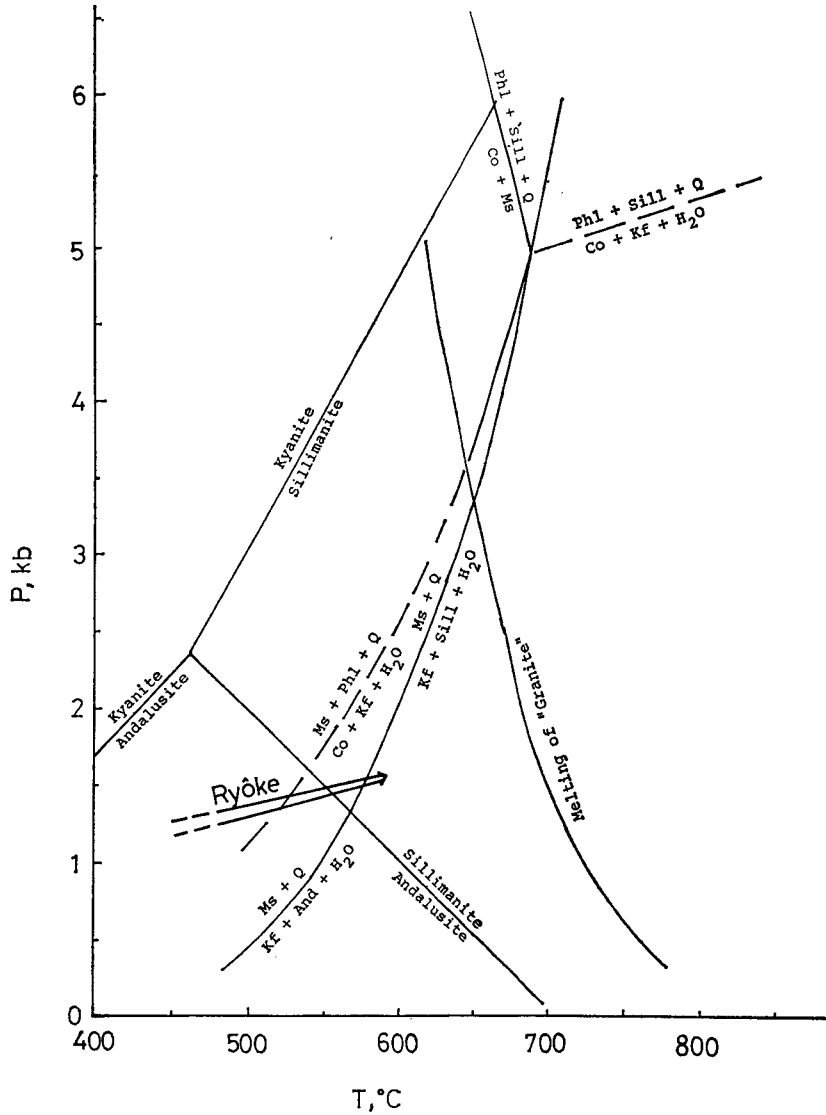


Fig. 28. Phase diagrams relevant to understanding the P-T condition of the Ryôke regional metamorphism. For details: see text.

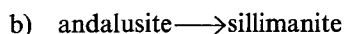
not have been the case in nature.

The implications of each reaction curve and transition curve for the Ryôke regional metamorphism are as follows respectively;



The experiment for this reaction has not been carried out so far, except for Mg-end members in a limited P-T field (SEIFERT, 1969). In the diagram (Fig. 28), the curve is high-hardedly extrapolated to lower-pressure and lower-temperature region by the present author.

In the Ryôke metamorphic terrain, this reaction has been used to define the cordierite isograd (HAYAMA, 1960, 1964a).



This transition is adopted to draw the first sillimanite isograd.



This reaction is used to define the second sillimanite isograd.

Therefore, the P-T condition of the Ryôke regional metamorphism can be shown schematically as represented as an arrow in the digram. From this figure one can deduce the P-T condition of the metamorphism. However, as above mentioned, in these reactions evaluation of $P_{\text{H}_2\text{O}}$ and solid solution effects of other end members in each mineral phase, especially Fe-end members, have not been taken into consideration. Both effects act as to reduce the temperature of the reaction, that is, of the metamorphism more or less. Thus, the net temperature of the Ryôke regional metamorphism would have been lower than that shown.

The upper limit of the pressure of the metamorphism

Pressure control could be yielded by reaction of the type: $\text{biotite} + \text{sillimanite} + \text{quartz} \longrightarrow \text{cordierite} + \text{K-feldspar} + \text{water}$. According to Schreinemakers analysis by SCHREYER and SEIFERT (1969), the reaction curve emanates from the point of $T=695^\circ\text{C}$, $P=5$ kb (invariant point), with flat positive slope.

Since the upper pressure stability of cordierite is markedly lowered by the incorporation of Fe^{+2} (SCHREYER, 1968; RICHARDSON, 1968), it was anticipated by SCHREYER and SEIFERT that the reaction curve is shifted to lower pressures in the more complex, Fe-bearing system. As the compositions of the ferromagnesian phases do vary with P and T, reaction curve will shift into a divariant field according to sliding equilibrium reaction.

In the rocks of the Toyone-mura area, the four phases of biotite, sillimanite, cordierite and K-feldspar occur as to be in equilibrium, thus they must be under P-T condition within the divariant field. Therefore, the upper limit of pressure of the metamorphism is restricted by 5 kb, the pressure of invariant point.

This situation is in good accordance with the statement of TURNER (1968) that

the pressure estimation of the Ryôke regional metamorphism by MIYASHIRO (1961) as to be 5 to 6 kb is too high.

7. Other physical conditions.

Water-vapour pressure and oxygen fugacity

In the metamorphic reactions, here concerned, dehydration plays an important role. Since these dehydration reaction have proceeded, the region where the metamorphism has taken place must have been permeable enough to let water and other volatile components, such as carbon dioxide, escape to out of the system.

On the other hand, as suggested by MIYASHIRO (1958), in general the high water-vapour pressure, if other factors remain constant, results in high oxygen fugacity, *vice versa*, low water-vapour pressure does in low oxygen fugacity. He also suggested that the ratio of $Fe^{+3}/(Fe^{+3} + Fe^{+2})$ in the constituent minerals reflects the oxygen fugacity when it is formed.

The very low $Fe^{+3}/(Fe^{+3} + Fe^{+2})$ ratios in these biotites would show the low oxygen fugacity at their formation, i.e., during the metamorphism. It follows that the water-vapour pressure would also have been relatively low. The very presence of graphite in these rocks indicates not so high f_{O_2} .

Recently TSUSUE and ISHIHARA (1974) insisted that the plutonism in the Ryôke zone took place under low oxygen fugacity condition, because of the poverty of oxide minerals and the absence of magnetite in the Ryôke plutonic rocks, such as gabbros and granitic rocks. Both HONMA (1974) and KANISAWA (1975), examined the chemical compositions of the mafic constituent minerals, mainly of biotites, of the granitic and metamorphic rocks, suggested that the Ryôke regional metamorphism and plutonism have occurred under the similar above mentioned conditions.

Formerly HAYAMA (1962) pointed out that the Ryôke regional metamorphism is characterized by both low solid pressure and low water-vapour pressure. The evidences, appeared in the rocks of the Toyone-mura area, also support this view.

8. Contact metamorphism

Contact metamorphism can be detected near the granite invasion. Mineralogically replacement of sillimanite by muscovite and growth of large porphyroblastic muscovite are observable as its results. ONO (1969b) clearly showed that modal muscovite in the metamorphic rocks increases toward the granite contact. Formation of muscovite requires potash and water, among others, and some part of them must have been derived from the granite. Release of water after the solidification of granite magma resulted in the circulation of hydrothermal solutions into the surrounding metamorphic rocks. The solution must have included much alkaline ions, especially of potassium. Post-magmatic potash metasomatism has been taken into account in the granite magmatism (ESKOLA, 1956).

9. Retrogressive metamorphism

Retrogressive metamorphism would take place at the time after the culmination of the metamorphism and at the ascending of the metamorphic belt. For the Ryôke metamorphic rocks, the retrogressive metamorphism has been revealed by KATADA (1967) and ISHIOKA (1974) for sedimentogeneous metamorphic rocks and by KUTSUKAKE (1974) for basic, gabbroic, rocks.

In pelitic rocks, usually observed phenomena are replacement of aluminum silicates by muscovite and of cordierite by pinitic minerals. Moreover, epitaxial muscovite is developed to replaced the cordierite. These reactions require water which has probably been derived from out of the system. In this connection, circulation of hydrothermal solution has been suggested during the retrogressive metamorphism (KUTSUKAKE, 1974).

X. Geological Situation of the Ryôke Zone Viewed from Petrological Aspects

As previously mentioned, the Ryôke regional metamorphism is characterized by low solid pressure and relatively high temperature, and its metamorphic condition is very similar to that of the contact metamorphism around granite. In this connection, SUGI, a pioneer of modern metamorphic petrology in Japan, has pointed out as early as 1933, that the Ryôke regional metamorphism has a character of contact metamorphism spread over in regional scale. Recently, staurolite-bearing mica schist was found by ASAMI (1971) from the Hazu area, about 70 km southwest to the Toyone-mura area. Accordingly, SUWA (1973) insisted that the Ryôke regional metamorphism should be divided into the two stages; the earlier one is of low to moderate pressure intermediate type, and the later one of andalusite-sillimanite type facies series of MIYASHIRO (1961) respectively. However, the association of staurolite-andalusite has been recorded in several contact aureoles around granite. As regard the Santa Rosa aureole in the Sierra Nevada (COMPTON, 1960), for example, in the outer zone staurolite is stable, but, in the inner zone it becomes unstable and is decomposed to cordierite and andalusite. Thus the presence of staurolite does not always imply the high-pressure condition in the metamorphism, but in some cases the low-temperature condition. Therefore, it is not necessary to divide the Ryôke regional metamorphism into two stages of the different natures. The metamorphism in the Hazu area probably underwent with slightly different condition from those of other areas in the Ryôke zone. But, its details are not known so far.

The fact that the sillimanite zone, the highest-grade zone of the Ryôke regional metamorphism is relatively wide in comparison with the other lower-grade zones, suggests the steep thermal gradient on both sides of the metamorphic terrain. And it also shows that the thermal structure of the metamorphism was of table-like form.

The temperature of the flat top of the "table" has probably been around 600°C or slightly lower.

The high-grade zone is occupied by the vast granitic intrusives of the older group (=pre-Nôhi granites), represented by the Tenryûkyô granite in the Chûbu district (RYÔKE RESEARCH GROUP, 1972) and the allied ones in the other districts. These granites can be regarded to have the most intimate connection with the regional metamorphism, and might have been the main source of the heat of the metamorphism.

It is also suggested that the Ryôke zone has been not so deep-seated region, but rather ascending one, from the following reasons; 1) the metamorphism occurred under low-pressure, 2) the metamorphic reactions are always of dehydration ones which easily take place at permeable areas for water.

HAYAMA (1962b) considered that the Ryôke zone might have been the rift part after the geosynclinal and there the regional metamorphism took place in intimate connection with the intrusions of the granitic magmas.

The fundamental geological features and petrological characteristics of the metamorphism must be due to the vast granitic intrusions at relatively shallow depth during or immediately after the ascending stage of the Honshû geosyncline. In this sense, the zone can not be thought as the down-buckled region of the orogenic belt. The general schema that the thick geosynclinal sedimentary rocks have been brought about to comparatively great depth and metamorphosed under the great load pressure and high temperature, can never be adopted to the Ryôke regional metamorphism. General upheaval of isogeotherm associated with the intrusions of the granitic magmas must have caused the low-pressure and high-temperature Ryôke regional metamorphism.

In this connection, at the south (~east) to the Ryôke zone, disposition of islands (rift zone) are supposed to have been in the geosyncline by ICHIKAWA (1970).

XI. Summary and Conclusions

The Ryôke metamorphic rocks in the Toyone-mura area, Aichi Prefecture, have been described in detail in regard to their geological, petrographical and mineralogical aspects, and the metamorphic conditions are discussed from the view-points of mineralogical equilibria and metamorphic reactions.

These metamorphic rocks are characterized by what they have been formed under the low solid pressure and relatively high temperature condition. The most typical mineral association in pelitic metamorphic rocks is of cordierite-K-feldspar, which is characteristic to the cordierite-K-feldspar hornfels facies defined by WINKLER (1967). However these rocks do not belong even to the orthoamphibole subfacies, its lower-temperature one, but do to the hornblende hornfels facies of TURNER (1958, 1968).

The pressure of the metamorphism is slightly higher than that of the usual contact aureole around the granite, and it is limited by 5 kb. Therefore, the Ryôke regional metamorphism must have taken place at relatively shallow depth, probably less than 10 km. It would have been caused by high heat flow with unusual steep geothermal gradient, which has probably been connected with the intrusions of the vast granitic magmas or the formation of the granitic magmas beneath the Ryôke zone.

This singular nature of the metamorphism must have reflected the special geological situation of the Ryôke zone; the general upheaval part at the time of the metamorphism. Since the time of the Honshû geosyncline, the region where now the Ryôke metamorphic terrain, has to be of upsidence, thereafter the granitic activities took place accompanied by the high-temperature regional metamorphism.

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Explanation of Plates

Plate 1

- 1: Concordant veins of the Tenryûkyô granite into the gneiss. 1 km northeast to Ôtani.
- 2: Banded gneiss, pygmatic-folded quartzo-feldspathic veinlets are developed. 500 m northwest to Urushijima.
- 3: Pelitic gneiss (upper, dark coloured part) and psammitic gneiss (lower, light coloured part), alternated each other. 300 m southeast to Sogawa.

Plate 2

Photomicrographs of the metamorphic rocks of sedimentary origin.

- 1: Gneiss (Specimen No. 68122005), cordierite-K-feldspar association. Crossed nicols.
- 2: Gneiss (Specimen No. 74032207), andalusite to sillimanite transition. Crossed nicols.
- 3: Gneiss (Specimen No. 68050202), muscovite breakdown to sillimanite. Crossed nicols.
- 4: Gneiss (Specimen No. 70092003), garnet-biotite-cordierite association. Open nicol.

Abbreviations: A: andalusite, B: biotite, C: cordierite, G: garnet, K: K-feldspar, M: muscovite, S: sillimanite, P: plagioclase.

The scale is common to all the microphotographs.

1



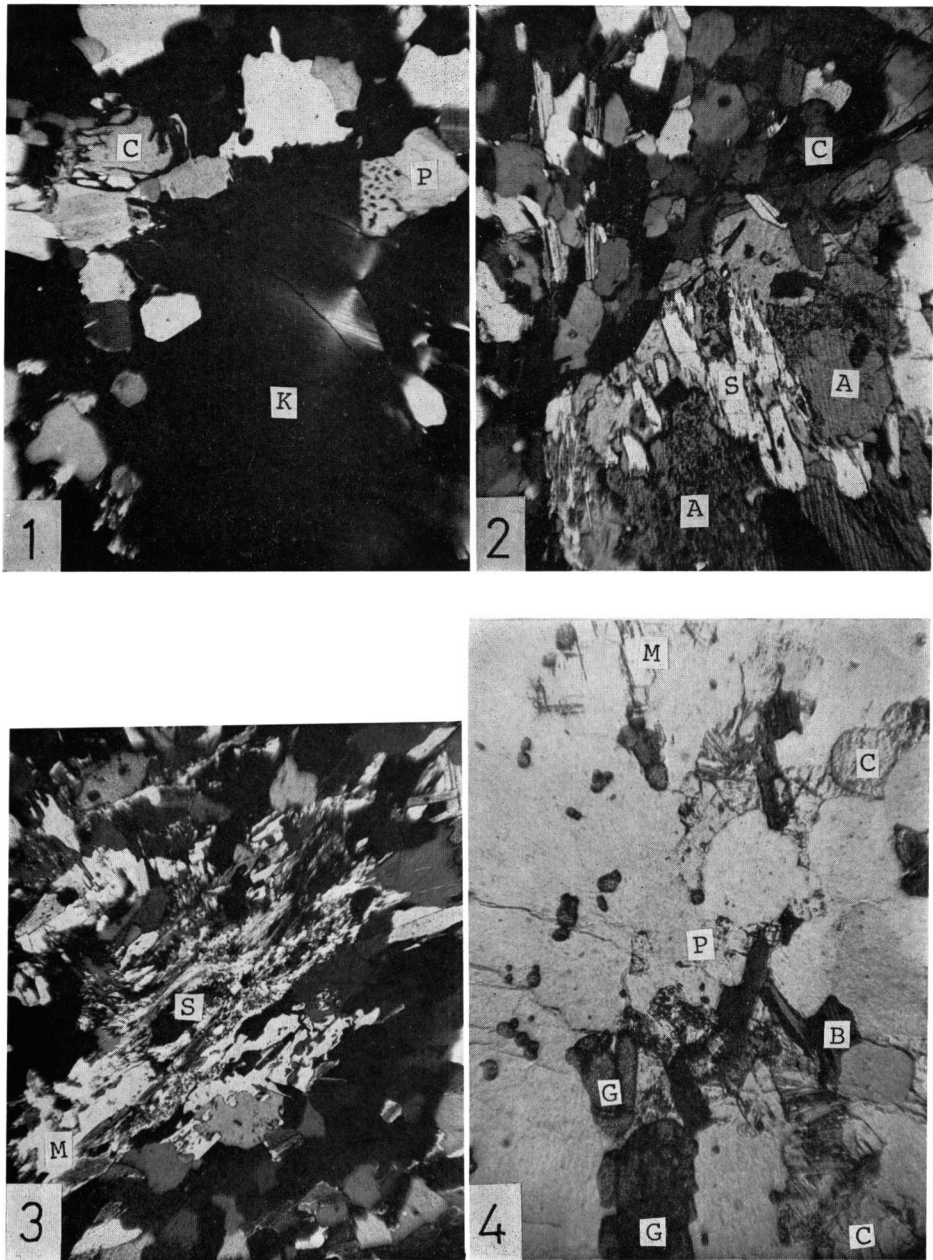
2



3



KUTSUKAKE: Ryôke Metamorphic Rocks in the Toyone-mura Area



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