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Regional Metamorphism of the Nishiki-chô District, Southwest Japan

By

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with 10 Tables, 30 Text-figures, and 1 Plate

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ABSTRACT: Regional metamorphism of the Nishiki-chô district on the east of Yamaguchi Prefecture has been investigated from geological and petrological points of view. The basement formations of this district consist of slightly metamorphosed rocks and crystalline schists. These are divided stratigraphically into two Groups, namely, the Nishiki Group (Lower to Upper Permian) and the Tsuno Group (presumably Carboniferous in the main), respectively, in descending order.

The metamorphic terrain is divided into three zones, A, B and C, on the basis of systematic mode of appearance of pumpellyite and amphiboles. Zone A is characterized by the assemblage pumpellyite-chlorite in basic and psammitic rocks. No schistosity and less recrystallization are characteristic. Zone B is characterized by the assemblage pumpellyite-actinolite in basic schists. Schistosity and lineation are well developed, recrystallization being almost complete. Zone C is characterized by the assemblages epidote-glaucophane and/or epidote-subcalcic hornblende in basic schists. Occurrence of garnet in pelitic and siliceous schists also characterizes this zone. Schistosity and lineation are well developed and recrystallization is complete.

The boundary surfaces between these metamorphic zones are nearly parallel to the bedding surface, and the metamorphic grade increases from the upper to the lower stratigraphic horizon. Zone A coincides with the whole of the Nishiki Group, zone B comprises the uppermost horizon of the upper formation of the Tsuno Group and zone C corresponds to other lower horizons of the Tsuno Group.

In the present metamorphic terrain, two phases of deformation can be detected. During the earlier phase, which is represented by the formation of the lineation L_1, progressive regional metamorphism grading from zone A to zone C might have taken place. The later phase corresponds to the deformation related to the formation of major folds. To this phase of deformation is also related the formation of tectonic slide, which is developed along the boundary zone between zones A and B showing different physical properties.

It is concluded that the metamorphites of the three metamorphic zones were formed by one and the same metamorphism, namely, the Sangun metamorphism. The facies series of the Sangun metamorphism in question runs from the pumpellyite-chlorite zone, through the pumpellyite-actinolite zone, to the epidote-glaucophane zone and/or the epidote-subcalcic hornblende zone in the order of increasing metamorphic grade, and corresponds to the high-pressure intermediate group in MIYASHIRO's classification.

Main constituent minerals are described and discussed genetically in some detail. Petrochemical properties of basic metamorphic rocks are also mentioned briefly. Bulk chemical compositions of 75 basic metamorphic rocks are presented.

CONTENTS

I. INTRODUCTION

Many isolated terrains composed of so-called phyllites or crystalline schists are distributed in the Inner Zone of Southwest Japan. The distribution of these terrains extends from the north Kyushu through the Chugoku province to the Hida marginal zone, suggesting the presence of a belt of regional metamorphism, that has been named the Sangun metamorphic belt (Fig. 1). This metamorphic belt has been known to consist of rocks characterized by mineralogical as well as structural features of common regional metamorphites. The metamorphic grade of the rocks ranges from the greenschist and/or the glaucophane-schist facies to the epidote-amphibolite facies in general. While, in some districts of this belt, the metamorphic rocks are intimately associated with "non-metamorphic" Paleozoic formations. Recently, it is becoming clear that rocks of these formations are not "non-metamorphic" in the strict sense, but are slightly metamorphosed to form such lower-grade metamorphic minerals as prehnite and pumpellyite. Accordingly, in order to clarify the geological as well as petrological development of the Sangun metamorphic belt, both the crystalline schist complex and the "non-metamorphic" Paleozoic formations should be treated from the systematic point of view. For keeping away confusion, the term "slightly metamorphosed" will be used for the "non-metamorphic" in the conventional sense.

Studies on the Sangun metamorphic belt, including the surrounding Paleozoic formations, began mainly in the regional geological researches to prepare geological maps of Japan (SUZUKI, 1906; OGURA, 1926; MURAYAMA, 1930; and others). After Warld War II, KOJIMA and his collaborators worked mainly on the stratigraphy and the geologic structure of the metamorphic terrains, many significant subjects having been clarified (KOJIMA, 1947, 1953; KOJIMA and SASAKI, 1950; KOJIMA et al., 1951;

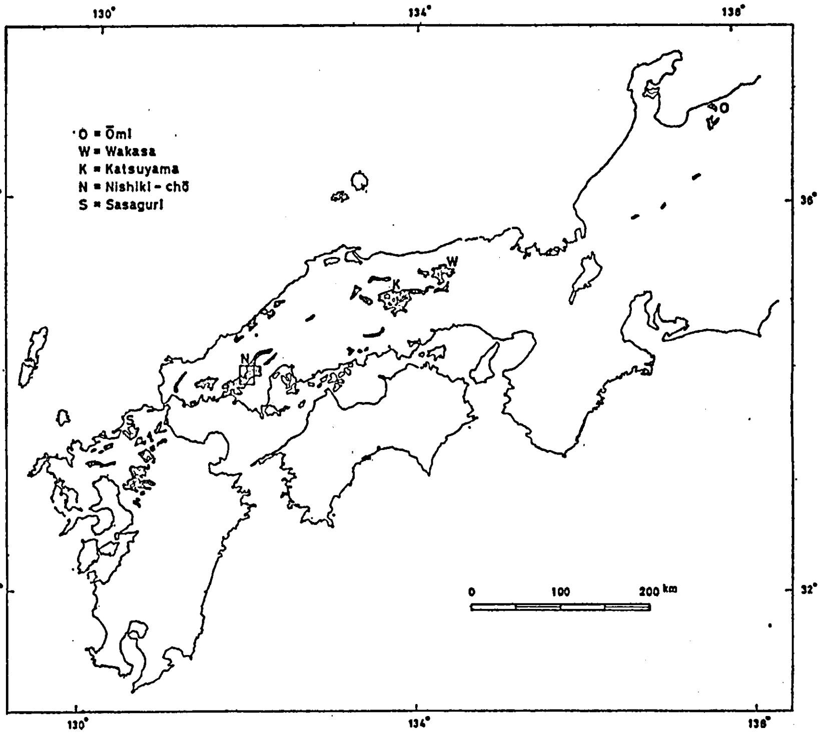

FIG. 1. Distribution of the Sangun metamorphic belt.

OKAMURA, 1953, 1963; OKAMURA and KOJIMA, 1951; YOSHINO, 1954; MITSUNO, 1959). Since 1958, when the zonal mapping of the Ômi district, Niigata Prefecture, was done by BANNO (1958), a number of papers dealing with petrology of the crystalline schists and/or the slightly metamorphosed rocks were published (HORIKOSHI, 1958; SEKI and MITSUNO, 1961; MIYAKAWA, 1961; TSUJI, 1964; NISHIMURA and NUREKI, 1966; HASHIMOTO, 1968a, 1968b; HASHIMOTO and IGI, 1970). By these works, wide-spread occurrence of such characteristic minerals as glaucophane (in a broad sense) and pumpellyite was clarified, and zonal classification of the metamorphic rocks has been tried in the Sangun metamorphic belt (including the surrounding Paleozoic formations). NUREKI (1969) reviewed a number of these studies from the stratigraphical, structural and petrological points of view and summarized that the crystalline schist complex and the slightly metamorphosed rocks were formed by different cycles of metamorphism, namely, the Sangun metamorphism and the burial metamorphism.

As to the Sangun regional metamorphism, however, there remain many puzzling problems not only on the nature of so-called glaucophanitic metamorphism devoid of jadeite-quartz assemblage and lawsonite but also on the geological and petrological relations between the crystalline schist complex and the slightly metamorphosed rocks. In order to settle these problems, more systematic projects on geology and petrology of both metamorphites are necessary and their mutual relationships should be analyzed.

The Nishiki-chô district in question satisfies enough conditions for above mentioned purposes. The author has been engaged in the studies on the Sangun metamorphic rocks (including the slightly metamorphosed ones) of the Nishiki-chô district since 1963. Some of the results obtained were published (NISHIMURA and NUREKI, 1966; NISHIMURA, 1971). In this paper, the author intends first to give data of stratigraphy, structure and petrology, and also to clarify their mutual relationships. Secondly, he intends to discuss on the nature of glaucophanitic metamorphism of the present district.

Acknowledgements: This work was carried out at the Hiroshima and the Yamaguchi Universities and completed at the Hiroshima University during his stay as a Visiting Research Associate, 1970. The author wishes to express his sincere gratitude to Prof. G. KOJIMA of the Hiroshima University for his kind advice and encouragement and also for critical reading of the manuscript. He is greatly indebted to Prof. H. YOSHIDA of the Hiroshima University, Prof. T. NUREKI of the Okayama University and Dr. I. HARA of the Hiroshima University for their helpful criticisms and suggestions. He is also indebted to Dr. Y. OKIMURA and Dr. K. SADA of the Hiroshima University for identification and dating of fusulinids, and to Dr. S. TAKENO of the same University for identification of sulfide and oxide minerals. His thanks are also due to Mr. K. HASHIKAWA for offering informations on the geology of the Mitake area in the present district, as well as to the members of the Petrologist Club of the Hiroshima University for their discussions.

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II. GEOLOGY

A. GEOLOGICAL SETTING

In Yamaguchi Prefecture, the older basement formations are well developed on the eastern part. They are zonally arranged in NE–SW trend. The basement rocks have been divided from north to south into the slightly metamorphosed Paleozoic formation, the Sangun crystalline schist complex and the Ryôke metamorphic rocks (Fig. 2). The former two are combined under the category of the Sangun metamorphites in a broad sense in this paper.

The Ryôke metamorphic rocks are regarded to be derived mainly from the Per-

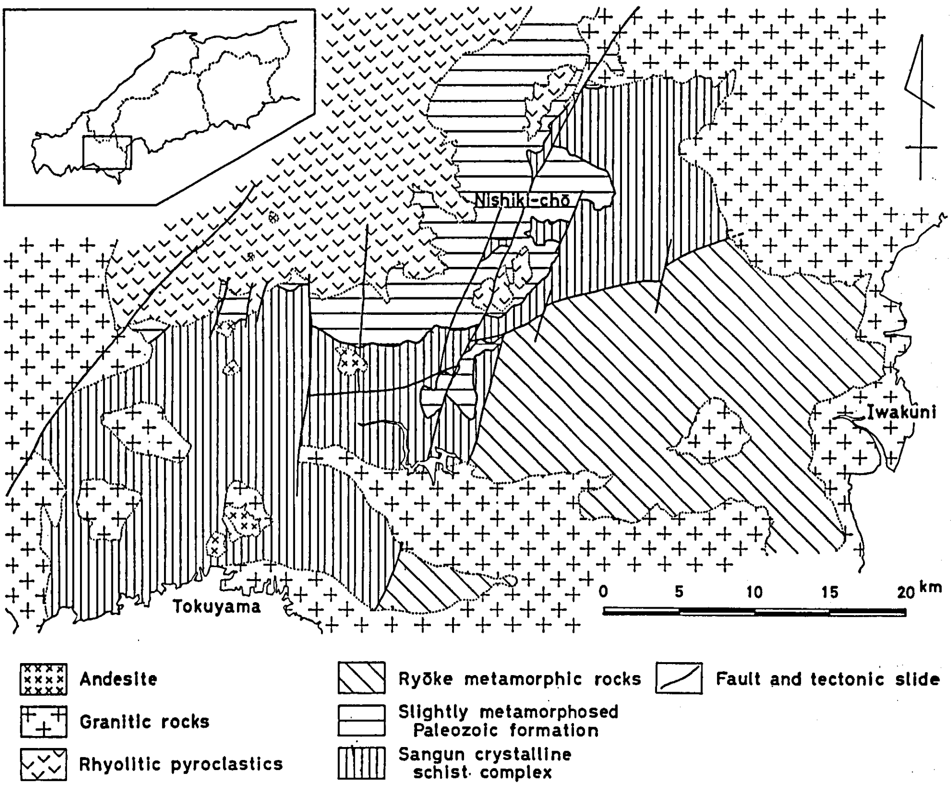


FIG. 2. Geological sketch map of the eastern part of Yamaguchi Prefecture.

mian sedimentary formation, named the Kuga Group, intimately associated with granitic rocks. OKAMURA (1968) classified the Ryôke belt of the eastern part of Yamaguchi Prefecture into five zones based on the increasing grade of metamorphism, namely, the Ryôke outer zone (weakly metamorphosed), schistose hornfels zone, transitional zone, banded gneiss zone and gneissose granodiorite zone[1]. The metamorphic facies series corresponds to the andalusite-sillimanite type in the sense of MIYASHIRO (1961).

The Sangun crystalline schist complex, named the Tsuno Group, consists mainly of pelitic, psammitic and basic schists, which can be regarded as derived mainly from Carboniferous sedimentary formations and from basic rocks. The schists would be formed under the metamorphic condition of the glaucophanitic metamorphism. The slightly metamorphosed Paleozoic rocks, which belong to the "central non-metamorphic" belt after KOJIMA (1953), are Lower to Upper Permian in age, and named the Nishiki Group. The rocks show features of weak metamorphism of the

1) The Ryôke outer zone and the schistose hornfels zone are shown in Fig. 2. The banded gneiss and gneissose granodiorite zones are widely developed to the south of the figured area.

regional type, which corresponds to the prehnite-pumpellyite metagreywacke facies.

The Sangun and the Ryôke metamorphic terrains show marked contrast in the lithological facies as well as in the character of metamorphism, and both belts are bounded by a fault named the Suetakegawa tectonic line with NNE–SSW trend and by a group of fault with E–W trend (KOJIMA, 1953; OKAMURA, 1963; NUREKI, 1966). On the other hand, the Sangun crystalline schist complex and the slightly metamorphosed Paleozoic formation have closely related geologic structure and the grade of metamorphism is continuous from one to another, both forming a single geologic system.

These basement rocks were overlain unconformably by Cretaceous volcanic formations consisting mainly of rhyolitic lava and pyroclastics and were intruded by batholithic bodies of Cretaceous granitic rocks. Andesitic volcanics, presumably Pleistocene, are sporadically distributed in the Sangun crystalline schist terrain (Fig. 2).

KOJIMA et al. (1968) described gneissic rocks found as xenoliths in the andesite of Mitakesan in the present district. According to them, these rocks cannot be correlated to the rocks of the Ryôke or the Sangun metamorphic complex, but would correspond to the Hida gneiss complex. They pointed out also that the occurrence of gneiss xenoliths testifies to the presence of sialic layer of the crust under the Sangun metamorphic formations.

The present district, which measures about 25 km in the N–S direction and 15 km in the E–W, is mainly occupied by the Sangun crystalline schist complex and the slightly metamorphosed rocks, and has been left unaffected by granitic rocks except for a few part of the northern area. Therefore, the Nishiki-chô district is one of the most important field to clarify geological as well as petrological problems on the Sangun metamorphic belt in Southwest Japan.

The geological map and profiles of the Nishiki-chô district are shown in Plate XV.

B. STRATIGRAPHY

KOJIMA (1953) summarized the stratigraphic succession of the Paleozoic formations, including the Sangun crystalline schists, of the eastern part of Yamaguchi Prefecture, as shown in Table 1. He stated that the upper formation should be rather affiliated to his "central non-metamorphic" zone than to the Sangun crystalline schist zone, being correlated lithologically to the Ota Group of the Akiyoshi area. The Tsuno Group, which had been proposed by KOJIMA et al. (1951) for the crystalline schist complex of this region, was divided into the middle and the lower formations. NISHIMURA and NUREKI (1966) pointed out the difference in stratigraphy and lithology between the upper Tsuno Group of the Nishiki-chô area and the Ota Group of the Akiyoshi area, and proposed the new name, the Nishiki Group, for the upper Tsuno Group defined by KOJIMA. They divided lithologically and stratigraphically the Paleozoic formations, including the crystalline schist beds as well as the slightly metamorphosed ones, into two Groups, which are subdivisible

TABLE 1. STRATIGRAPHY OF THE PALEOZOIC FORMATIONS OF THE EASTERN PART OF YAMAGUCHI PREFECTURE

KOJIMA (1953)		NISHIMURA and NUREKI (1966)	
(Ota Group)	Upper formation	Nishiki Group	Upper formation Middle formation Lower formation
Tsuno Group	Middle formation Lower formation	Tsuno Group	Upper formation Lower formation

into five formations, as shown in Table 1.

Afterward, the author has been engaged in the geological survey over wider area. The stratigraphic succession of the crystalline schist and slightly metamorphosed formations of the Nishiki-chô district has been tentatively established. Fig. 3 shows the generalized stratigraphic columnar section compiled from many sections obtained along typical routes.

The following is a summarized description of the stratigraphy of the Paleozoic formations of the present district in ascending order.

1. *Stratigraphy of the Tsuno Group*

The Tsuno Group which consists of the crystalline schist complex, can be lithologically divided into two formations, according to the division of KOJIMA (1953). Total thickness of the Group is estimated at about 1,700 m or more in this district.

a). The lower formation: This formation consists of alternating beds of psammitic and pelitic schists, especially characterized by thick beds of psammitic schists (Tl-2 and Tl-4). In these rocks, such rock structures as schistosity, compositional banding, cleavage and lineation are well developed and recrystallization is almost complete. However, porphyroblastic crystals of plagioclase have not been found in any rocks.

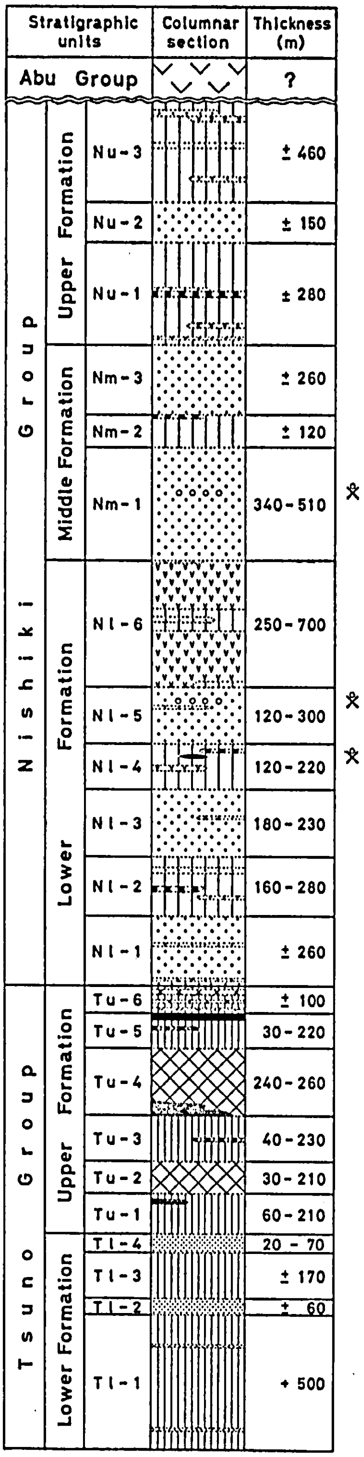
This formation represents the lowest portion of the basement formations in this district, overlain conformably by the upper formation. Because its lower limit is not exposed, real thickness of this formation cannot be estimated. As far as the surveyed area is concerned, it may attain about 800 m.

b). The upper formation: This formation is mainly composed of basic schists accompanied with ultramafic rocks (mainly serpentinite), pelitic schists, siliceous schists and calcareous schists. The formation is characterized by the predominance of basic schists and by the disappearance of psammitic schists, which is characteristic in the lower formation. Owing to the presence of a tectonic slide as mentioned later, upper limit of this formation can be scarcely ascertained. The thickness of the upper formation exceeds 900 m, as far as the formation is now exposed.

The upper formation is lithologically subdivided into the following six members, Tu-1, Tu-2, ... and Tu-6, in ascending order. As calcareous schists occur characteristically only in Tu–5 throughout the district, they can be used as key beds on the field.

Basic schists, which occupy the main part of Tu–2 and Tu–4, are generally green to dark green, medium-grained and massive. Schistosity and lineation are not so distinct as in pelitic schists. On the map the body of basic schists shows lenticular or amoeboid shape, being concordant or subconcordant with surrounding schists of sedimentary origin. On the other hand, basic schists in Tu–6 are pale green, fine-grained and schistose, occurring often as thin layers intercalated into pelitic schist beds. Although there had been several opinions as to the origin of these two types of basic schists in this district, the author (1971) discussed the relationship of these two types petrochemically, and concluded that the basic schists of the Tsuno Group are derived from such intrusives as sills.

Among six members of the Tsuno Group,



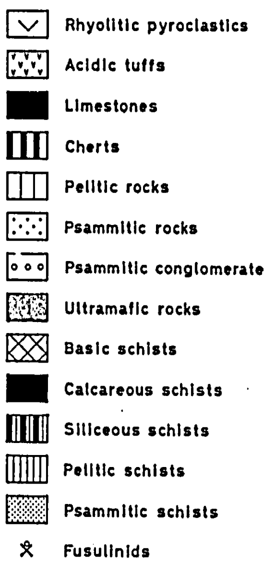


FIG. 3. Generalized stratigraphic columnar section of the Paleozoic formations of the Nishiki-chô district.

members from Tu-1 to Tu-4 are well recrystallized, and distinct schistosity and lineation are observed in pelitic schists. In the members Tu-5 and Tu-6, however, we can recognize that the degree of recrystallization tends to become lower and at the same time, schistosity and lineation become less prominent with approaching to the upper horizon.

2. *Stratigraphy of the Nishiki Group*

Slightly metamorphosed Paleozoic formations, which widely occur in the Nishiki-chô district, were named the Nishiki Group by NISHIMURA and NUREKI (1966). This Group is characterized by the predominance of psammitic rocks, intercalated with pelitic rocks and acidic tuffs. The lowest part of this Group is cut by a tectonic slide as mentioned later, while the upper parts are unconformably overlain by rhyolitic pyroclastics of the Cretaceous age. Total thickness of the Nishiki Group can be estimated at 2,900 to 3,900 m.

The Group can be lithologically divided into three formations, namely, the upper, middle and lower formations, which are conformable to each other. These formations can be subdivided into many members as shown in Fig. 3. Typical stratigraphical succession of the Group can be observed at Suma–Hisage–Ogoya route.

a). The lower formation: This formation is mainly made up of psammitic rocks, pelitic rocks and acidic tuffs, accompanied by chert, schalstein, limestone and conglomerate as subordinate members. It must be noticed that, in this formation, pale-green acidic tuffs occur predominantly. The thickness of this formation attains to 2,100 m in maximum, though it is fairly variable from place to place.

Acidic tuffs occur in Nl-2 and Nl-4 in small amount and in Nl-6 abundantly. They are alternated with pelitic rocks. They are pale green to pale bluish-green, fine-grained and hard. Phenocrysts of quartz and feldspars are rarely found, and the groundmass shows flow structure on the thin section. The chemical composition is rhyolitic after NISHIMURA and NUREKI (1966).

Psammitic rocks, which occur mainly in Nl-1, Nl-3 and Nl-5, are dark greenish-gray to dark gray, medium- to coarse-grained and massive. Graded bedding, convolute laminae and angular chips of slate are often observed in these rocks. Pelitic rocks, occurring in Nl-2 and Nl-4, are black and fine-grained. In the rocks of Nl-1 and Nl-2, lineation and intraformational folding are weakly developed.

In Nl-4 on the north of Deai, lense-shaped beds of schalstein accompanied with limestone and chert are found in places. Some fusulinids have been found from the limestone. Psammitic rocks of Nl-5 are partly accompanied by conglomerate on the north of Hirose and at the river side to the south of Hisage. The matrix of these conglomerates is psammitic, and the pebbles consist mainly of monzonitic granophyre, limestone, psammitic rock and pelitic rock, which are from about a head of cow to a red bean in size. Fusulinids are also found in limestone pebbles of the conglomerates. These fossils will be described in the later section.

b). The middle formation: This formation is mainly composed of alternated beds of psammitic and pelitic rocks, and is characterized by the predominance of psammitic rocks. The thickness is estimated at 720 to 890 m. In Nm-1 on the north of Kajibata, psammitic conglomerate close to that of Nl-5 occurs. Recently, A. FUJII (oral communication) of the Kyushu University also found fusulinid from its limestone pebbles.

c). The upper formation: This formation is mainly made up of pelitic and psammitic rocks and is subordinately accompanied by acidic tuff and red shale. The formation is characterized by the predominance of pelitic rocks. As Cretaceous rhyolitic pyroclastics overlie unconformably the formation, the thickness cannot be precisely determined. It exceeds, however, 890 m as far as now exposed.

The lithological character of the middle and upper formations is generally similar to that of the lower formation as described above. Although rocks of the Nishiki Group are very weakly recrystallized throughout the whole formations, extent of recrystallization becomes weaker with proceeding to the upper stratigraphic horizon.

3. *Age of original rocks*

We have no direct evidences to define the age of original rocks of the Sangun crystalline schist complex. However, the author found recently fusulinids at three localities, where occur rocks belonging to the members Nl-4 and Nl-5 of the lower formation of the Nishiki Group. FUJII (oral communication, 1970) also found fusulinid from limestone pebbles in psammitic rocks corresponding to the member Nm-1 on the north of Kajibata[1]. These are summarized in Table 2.

TABLE 2. FUSULINIDS OF THE NISHIKI-CHÔ DISTRICT

Locality	North of Deai (Nl-4)	North of Hirose (Nl-5)	South of Hisage (Nl-5)	North of Kajibata (Nm-1)
Occurrence	Limestone accompanied with schalstein	Limestone pebble of conglomerate	Limestone pebble of conglomerate	Limestone pebble of psammitic rock
Fossil	*Schwagerina*? sp. *Triticites* sp.	*Pseudofusulina* sp. *Parafusulina* sp. *Triticites*? sp.	*Schwagerina*? sp. *Pseudofusulina*? sp.	*Lepidolina* cf. *multiseptata multiseptata**
Zone	Upper part of *Pseudoschwagerina* zone	Lower part of *Parafusulina* zone	Lower part of *Parafusulina* zone	*Yabeina-Lepidolina* zone

* After A. FUJII (oral communication, 1970)

As seen from the table, the majority of the lower formation of the Nishiki Group correspond to the Lower to lower-Middle Permian in age and the middle formation of the Group to the Upper Permian. While, *Fusulinella*? sp. was also found from small pebbles contained in limestone of Nl-4 and from those in limestone pebbles

1) The auther is grateful to Mr. A. FUJII of the Kyushu University for permission to print his data which have not been published yet.

of psammitic conglomerate of Nl-5 at Hirose. Therefore, it is possible to regard that some of the lower formation of the Nishiki Group correspond to the Upper Carboniferous in age. The Tsuno Group which is stratigraphically lower than the Nishiki Group, therefore, may correspond to the Upper and/or Lower Carboniferous or the older age.

In weakly metamorphosed Paleozoic formations of Okayama Prefecture, TERAOKA (1958, 1959) discovered some fossils indicating the *Millerella* zone from limestone lenses, and HASHIMOTO (1968a) also found some fusulinids and plant fossils indicating the Upper Carboniferous to Lower Permian in age from limestone and black shale beds. Although the fossil-bearing formations in question were estimated to be situated on the upper stratigraphic horizons than the Sangun crystalline schist formations, it is still questionable whether the former lies conformably or tectonically on the latter.

Judging from these data, it may be concluded in the Chugoku province that original rocks of the weakly metamorphosed Paleozoic rocks are of Upper Carboniferous or Lower Permian to Upper Permian in age, while those of the Sangun crystalline schists are mostly of Upper and/or Lower Carboniferous or older.

C. GEOLOGIC STRUCTURE

Geologic structure of the crystalline schists and that of the slightly metamorphosed rocks of the Nishiki-chô district are closely related to each other. For the purpose of clarifing geologic structure, with special reference to structural differences between the crystalline schist terrain and the slightly metamorphosed one, mesoscopic and macroscopic structures will be described and discussed genetically.

1. *Rock structure*

a). Crystalline schists (Rocks of the Tsuno Group): The most predominant and principal foliation surface in the crystalline schists of this district is represented by compositional banding or lithologic layering in the sense of TURNER and WEISS (1963). The surface is generally correlated to the bedding surface of original rocks. This is termed S_1. S_1 is well developed commonly in pelitic, psammitic and siliceous schists. While, it is less developed or, in some cases, completely lacking in basic schists, especially in those of larger size. As the second planar structure, here termed S_2, fracture cleavage in the sense of DE SITTER (1956) can be observed. This surface S_2 is accompanied by small scale fold and cuts across S_1 at high angles.

Two kinds of linear structure can be recognized at least in the crystalline schists of this district. One of these, here termed L_1, is the lineation defined by preferred orientation of prismatic metamorphic minerals and by the intersection of S_1 and S_2. It is commonly observed as distinct streations on S_1. Another is the lineation that is represented as grooves on S_1. This lineation clearly cuts L_1 at nearly right angle in most cases. The lineation is termed L_2, produced later than L_1. Kink band is often formed in the crystalline schists of the upper horizon without regard to the kind of rocks. Axis of kink band is nearly parallel to L_2.

b). Slightly metamorphosed rocks (Rocks of the Nishiki Group): In the slightly metamorphosed rocks of this district, predominant surfaces are those of bedding, fracture and joint. Bedding surface that is observed as the most predominant planar structure, is termed S_1 and can be recognized by alternation of different lithologic units. Some sedimentary structures such as bedding plane, graded bedding, convolute laminae and so on are well preserved, and are conspicuous in the alternated parts throughout the whole formations. Cleavage structures are not formed in the slightly metamorphosed rocks.

Linear structure is weakly formed in the pelitic rocks of the lower formation of the Nishiki Group and is observed as grooves on the bedding surface S_1. This lineation, showing the same style as L_2 in crystalline schists, is also termed L_2. No lineation corresponding to L_1 in crystalline schists is formed in these rocks.

Kink band is also formed in the rocks of the lower formation of the Nishiki Group. Such fracture structures as wedges and telescoping in the sense of CLOOS (1961) conspicuously develop in the rocks neighbouring the tectonic slide and axial parts of large scale folds. The scale is variable and mostly ranges from a few centimeters to ten meters. Fracture planes, along which actual displacement occurred, intersect the bedding surfaces at low angles.

2. *Major fold and phase of deformation*

Geologic structure of the Nishiki-chô district is shown in Fig. 4. Major folds, showing anticlinal and synclinal structures, are remarkable, showing gentle wavy form in the present district. The wave length of the folds is 5 to 7 km and axes of folds are roughly horizontal with nearly E–W trend. It is noteworthy that the folding structures of the crystalline schist beds and the slightly metamorphosed ones are co-axial. Detailed structural analysis was shown in the previous paper (NISHIMURA and NUREKI, 1966). A recumbent fold has also been detected in the Mitake area in this district. The axial plane of this fold coincides with the bedding plane of surrounding rocks and dips to the north at a moderate angle. These structures distinctly regulate the distribution of the crystalline schists and the slightly metamorphosed rocks, that is, the former is exposed at the anticlinal region, while the latter is at the synclinal one (Fig. 4 and also Plate XV).

NISHIMURA and NUREKI (1966) analyzed statistically mutual relationship between such mesoscopic structural elements as S_1, L_1 and L_2 and macroscopic structures of the central part in this present district. According to them, the direction of anticlinal and synclinal axes coincides with that of βs_1, which is represented by the pole of great circle girdle of S_1-pole diagram, and with the maximum for L_2. Moreover, they pointed out that the L_1-diagram shows two prominent maxima lying on a great circle girdle, which coincides with the great circle girdle of S_1-pole diagram. In addition to former analyses, an orientation diagram for the axes of kink band in the crystalline schists of the Deai area is newly shown in Fig. 5 with diagrams for other

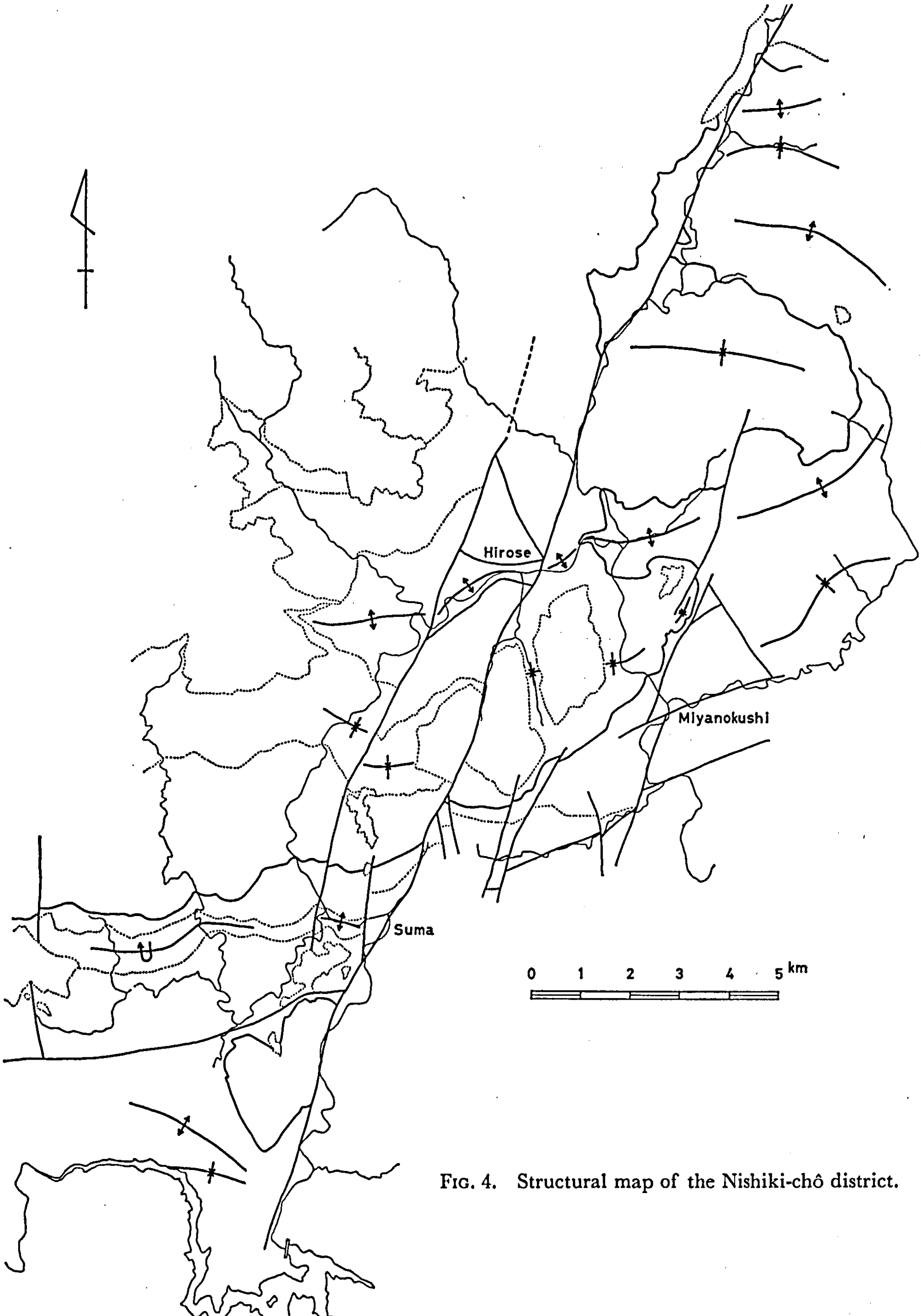


FIG. 4. Structural map of the Nishiki-chô district.

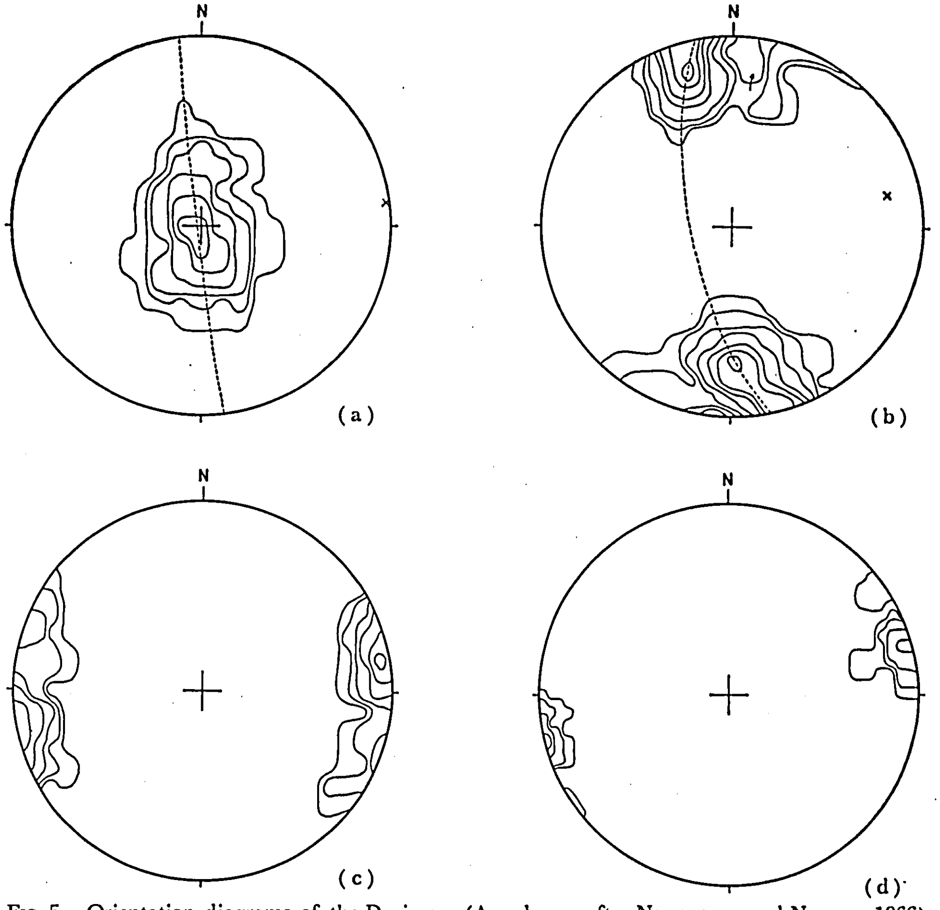


FIG. 5. Orientation diagrams of the Deai area (A_3 subarea after NISHIMURA and NUREKI, 1966).
(a) S_1-pole diagram. A broken line represents π-circle for S_1 and a cross represents βs_1. Contours: 18-13-7-4-2-1%.
(b) L_1-diagram. A broken line represents the general orientation of L_1 and a cross represents the pole. Contours: 21-14-10-4-2-1%.
(c) L_2-diagram. Contours: 30-20-12-7-4-1%.
(d) Orientation diagram for the axes of kink band. Contours: 60-30-13-8-4%.

elements (those of A_3 subarea after NISHIMURA and NUREKI, 1966). The diagram (Fig. 5-d) has a distinct maximum, the direction of which coincides nearly with those of βs_1 and the maximum for L_2.

From these analyses, two phases of deformation can be distinguished in this district. The earlier phase, here termed the L_1-phase, is represented by the formation of the lineation L_1 shown as the preferred orientation of prismatic metamorphic minerals and as the intersection of S_1 and S_2 as well. During this phase would have taken place progressive regional metamorphism grading from zone A through zone B to zone C as shown later. The later phase, here termed the L_2-phase, is characterized by the formation of the lineation L_2 shown as grooves on S_1. The maximum for L_2 coincides with β for S_1 and, furthermore, with the maximum for kink band axis. Accordingly, the L_2-phase may correspond to the deformation related to the formation of major structures (anticlines and synclines). In this phase, mechanical state of rocks would have been fairly brittle, specifically in the weakly metamorphosed rocks. This feature is clearly shown at the axial parts of syncline (NISHIMURA and NUREKI, 1966; Fig. 7). Occurrence of wedges and telescoping structures is also in harmony with this view.

3. *Structural relation between the Nishiki and the Tsuno Groups*

KOJIMA (1947, 1953) proposed suggestive ideas on the relation between the Sangun metamorphic zone (the crystalline schist terrain or the Tsuno Group in this paper) and the "central non-metamorphic" zone (the slightly metamorphosed rock terrain or the Nishiki Group in this paper) in the eastern part of Yamaguchi Prefecture. The following three types of relation were mentioned by him.

(1) The "non-metamorphic" formations overlie conformably the metamorphic formations.

(2) Shear-zone develops between the "non-metamorphic" and the metamorphic belts.

(3) The "non-metamorphic" terrain thrusts over the metamorphic terrain.

The Kitayama over-thrust, formerly named by KOJIMA (1947), corresponds to the third item above mentioned. The thrust line traverses Kitayama in this district with nearly E–W trend, dipping to N at moderate angles and the thrust was correlated to the Saigatao tectonic line in the Mine region in the western part of Yamaguchi Prefecture (MATSUMOTO, 1951; KOJIMA, 1953). As to the age of formation of the Kitayama over-thrust, KOJIMA (1953) stated that it is the pre-Middle Cretaceous.

The author has been engaged in the geological survey of wider area and clarified that there is universal relationship of tectonic disturbance between the Tsuno and the Nishiki Groups. The disturbance is represented by distinct sheared zone[1)], which is also the zone of discontinuity in lithology as well as metamorphic grade. The tectonic zone is macroscopically concordant to the trend of surrounding rocks and is traceable through the whole area in question as shown in Fig. 4. Shape of the tectonic line on the map is distinctly related to the disposition of major anticlinal and synclinal structures. Therefore, it is suggested that the zone was formed in close genetical connection with the major folding. At the exposures, the hanging-wall is the slightly metamorphosed rocks of the lower formation of the Nishiki Group, and the foot-wall is the crystalline schists, referable to the upper formation of the Tsuno Group. Moreover, at the boundary zone of the Tsuno and the Nishiki Groups, horizons of both Groups coming in contact with each other vary from place

1) The sheared zone is clearly exposed in the Mitake and the Fukasu areas. Zone of fault clay is 50 cm or less, but surrounding rocks are widely fractured.

to place as shown in the previous paper (NISHIMURA and NUREKI, 1966; Table 6) (see also, Plate XV). Therefore, it seems that, along the tectonic zone, wedging and telescoping on a larger scale would have been taken place between both Groups.

Judging from these structural evidences, the tectonic zone should not be regarded as over-thrust but as such a type of tectonic slide as defined by FLEUTY (1964). This tectonic slide is believed to be simultaneous with the tectonic movement related to the formation of major fold, namely, L_2-phase deformation, and may have been presumably reactivated in later geologic age. The Kitayama over-thrust after KOJIMA is equivalent to this tectonic slide.

Accordingly, stratigraphic relationship between the Tsuno and the Nishiki Groups is belived to be conformable in the original state of deposition. The stratigraphic discontinuity, now recognized, originated in the L_2-phase of deformation.

III. PETROLOGY OF REGIONAL METAMORPHIC ROCKS

A. SCHEME OF MINERALOGICAL ZONING

As described in the preceding chapter, the crystalline schist complex is tectonically overlain by the slightly metamorphosed rocks. In the slightly metamorphosed rocks, formerly considered to be "non-metamorphic", such metamorphic minerals as white mica, chlorite, pumpellyite and stilpnomelane are commonly found. Degree of recrystallization and grade of metamorphism increase from the upper to the lower horizon in the stratigraphic succession.

It is possible to establish a consistent scheme of mineralogical zoning of metamorphic terrain throughout the whole older basement, including the crystalline schist terrain as well as the slightly metamorphosed one, on the basis of systematic mode of appearance and disappearance of pumpellyite and amphiboles. The Nishiki-chô district can be divided into three zones, namely, zone A, zone B and zone C, in the order of increasing metamorphic grade. Schematic figure showing the stability of minerals in each zone is shown in Fig. 6.

Zone A: This zone is characterized by the assemblage pumpellyite-chlorite in basic and psammitic rocks. No schistosity and less recrystallization are characteristic. Zone A coincides practically with the Nishiki Group as a whole.

Zone B: The assemblage pumpellyite-actinolite is characteristic in basic schists. Schistosity and lineation are well developed. Metamorphic recrystallization is almost complete, but some relic clinopyroxenes are preserved in a few basic schists in the lowest grade part of this zone. Zone B comprises the uppermost horizon in the upper formation of the Tsuno Group.

Zone C: This zone is characterized by disappearance of pumpellyite and by appearance of either crossite or subcalcic hornblende in basic schists. Occurrence of garnet in pelitic as well as in siliceous schists also characterizes this zone. Schistosity and lineation are well developed and metamorphic recrystallization is complete. Zone C includes other lower stratigraphic horizons of the Tsuno Group.

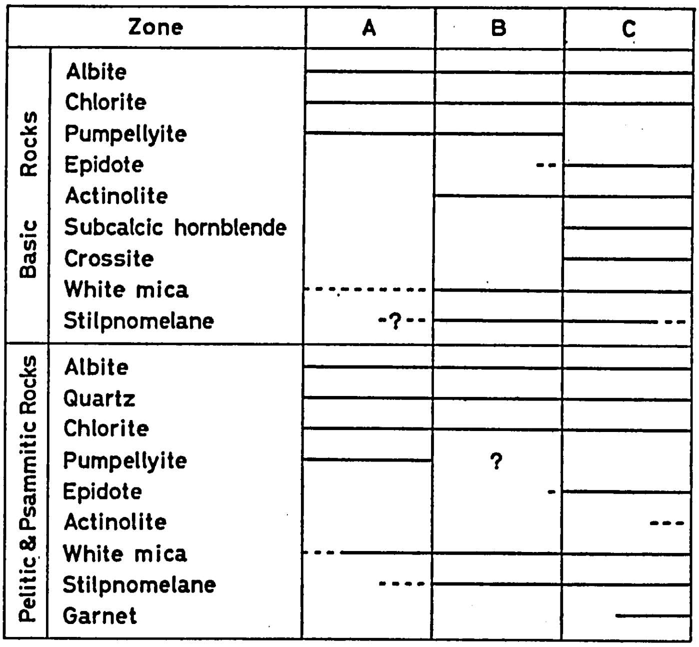


FIG. 6. Mineralogical variation with increasing grade of metamorphism in basic, pelitic and psammitic rocks of the Nishiki-chô district. Broken line indicates the mineral being uncommon.

NISHIMURA and NUREKI (1966) divided tentatively a part of the Nishiki-chô district into two zones, namely, zone I and zone II. It was pointed out by them to occur the assemblage pumpellyite-actinolite in lower grade part of zone II. Thereafter, occurrence and universality of the assemblage pumpellyite-actinolite have been clarified by examination in widely enlarged area. Correlation of notation between the previous and the present papers is as follows: Zone A corresponds to zone I. Zone B corresponds to the lower grade part of zone II and zone C to the higher grade part of zone II.

B. SPATIAL RELATIONS OF METAMORPHIC ZONES

On the basis of distribution of characteristic metamorphic minerals, the present metamorphic terrain, including both of the slightly metamorphosed terrain and the crystalline schist one, is divided into three zones, as shown in Fig. 7. Boundary surfaces between these metamorphic zones are nearly parallel to those of stratification, and metamorphic grade increases from the upper to the lower horizon in the stratigraphic succession. Therefore, each zone practically coincides with stratigraphic units, that is, zone A corresponds to the Nishiki Group as a whole, zone B to the uppermost horizon of the upper formation of the Tsuno Group and zone C to other lower stratigraphic horizons of the Tsuno Group.

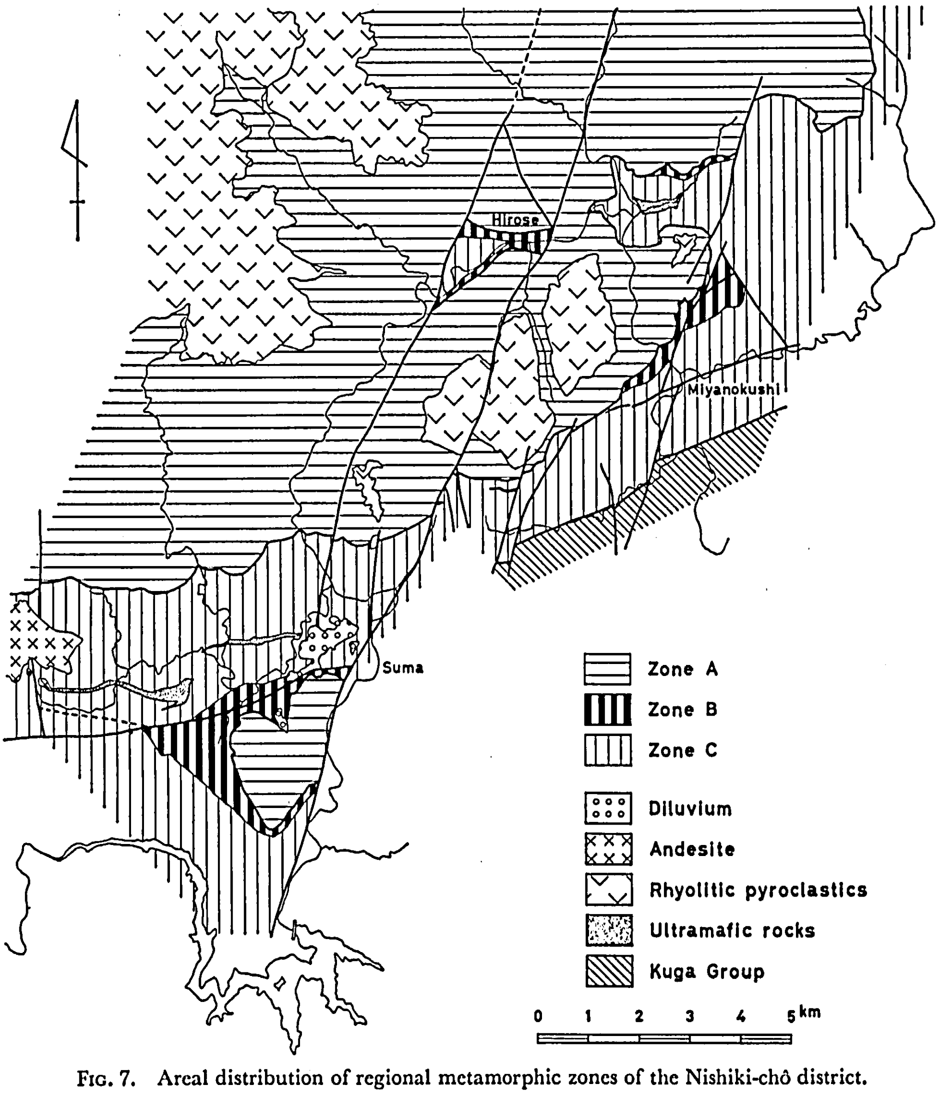


FIG. 7. Areal distribution of regional metamorphic zones of the Nishiki-chô district.

Distribution of these three zones is shown in Fig. 7. As seen from the figure, the disposition on the map of each zone is clearly related to such geologic structure as major folds and the tectonic slide. It is worthy of note that zone B is lacking in some places. As discussed in the preceding chapter, stratigraphic succession of the present district would probably be continuous before the formation of main geologic structures. Under such condition, progressive regional metamorphism grading from zone A through zone B to zone C would have taken place during the L_1-phase of deformation, when rocks of zones B and C changed to schistose rocks, while rocks of zone A remained rather massive. When the tectonic movement related to the major folds took place in the L_2-phase of deformation, the tectonic slide was formed along the boundary zone between zone A and zone C, which represents a zone of discontinuity in mechanical property of rock, and wedging and telescoping of zone B have resulted. Therefore, the direct contact of zone A and zone C does not imply continuous change of metamorphic grade from zone A to zone C but the wedging of zone B along the tectonic zone.

C. Metamorphic Rocks of Zone A

Metamorphic rocks of zone A, which compose the Nishiki Group, are derived mainly from pelitic, psammitic and acidic pyroclastic rocks. Basic pyroclastic rocks are found very rarely. These rocks are apparently unmetamorphosed to the naked eye, having few structural features of common regional metamorphic rocks such as schistosity and lineation. Under the microscope, however, we can observe metamorphic minerals such as white mica, chlorite, stilpnomelane and pumpellyite in basic, psammitic and pelitic rocks, though original texture and original minerals have been preserved as relics in most rocks. Pumpellyite does not found in pelitic rocks. Neither prehnite nor actinolite, however, has been found from any rocks of this zone. The metamorphic minerals are generally very fine-grain and degree of recrystallization increases a little toward the lower stratigraphic horizon in this zone.

Mineral assemblages observed in rocks of zone A are as follows:

Pelitic and psammitic rocks

1) White mica-chlorite-albite-quartz
2) White mica-chlorite-pumpellyite-albite-quartz
3) White mica-chlorite-stilpnomelane-albite-quartz
4) White mica-chlorite-pumpellyite-stilpnomelane-albite-quartz

} ± calcite

Basic rocks

1) Chlorite-albite
2) Chlorite-white mica-albite
3) Chlorite-pumpellyite-albite

} ± calcite, quartz

Although, owing to the scarcity of basic rocks, mineral paragenesis of basic rocks could not be sufficiently examined, it seems that prehnite and actinolite do not occur in any rocks of zone A. Pumpellyite and chlorite would have probably been formed by the decomposition of calcic plagioclase and clinopyroxene according to the following chemical reaction:

$$\underset{\text{anorthite}}{7CaAl_2Si_2O_8} + \underset{\text{clinopyroxene}}{12Ca(Mg, Fe)Si_2O_6} + 11CO_2 + 15H_2O$$
$$= \underset{\text{pumpellyite}}{2Ca_4Al_5(Mg, Fe)Si_6O_{23}(OH)_3 \cdot 2H_2O} + \underset{\text{chlorite}}{2(Mg, Fe)_5Al_2Si_3O_{10}(OH)_8}$$
$$+ \underset{\text{calcite}}{11CaCO_3} + \underset{\text{quartz}}{20SiO_2} \cdots\cdots (1)$$

Mineral assemblages of basic rocks can be represented by the ACF diagram (Fig. 8).

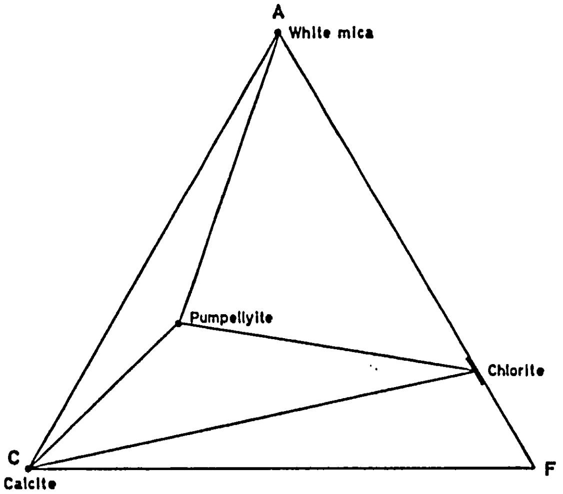


FIG. 8. ACF diagram for basic metamorphic rocks of zone A.

The mineral paragenesis of the figure indicates that the metamorphic condition of this zone may be intermediate between that of the prehnite-pumpellyite assemblage and that of the pumpellyite-actinolite assemblage. Zones of similar mineral paragenesis were described in zone Ib of the Kanto Mountains (SEKI, 1961), in the pumpellyite zone of the Chichibu belt of western Shikoku (HASHIMOTO and KASHIMA, 1970) and in the pumpellyite zone of the Tamba Plateau (HASHIMOTO and SAITO, 1970).

D. METAMORPHIC ROCKS OF ZONE B

Metamorphic rocks of zone B are derived from pelitic, siliceous and basic rocks. Recrystallization of these rocks is more advanced in this zone than in the previous zone. Structural features such as schistosity and lineation are well developed, and most rocks of this zone are crystalline schists. Relic minerals of clinopyroxene, however, are locally observed in basic schists. Those minerals will be described in chapter IV.

Metamorphic minerals of zone B are quartz, albite, white mica, chlorite, calcite, stilpnomelane and epidote in pelitic and siliceous schists, and albite, chlorite, white mica, stilpnomelane, pumpellyite, actinolite and epidote in basic schists. Stilpnomelane, pumpellyite and actinolite are abundant, whereas epidote is rare in this zone. Zone B is characterized by the appearance of actinolite in basic rocks.

The following mineral assemblages are observed in rocks of zone B:

Pelitic and siliceous schists

1) White mica-chlorite-albite-quartz
2) White mica-chlorite-stilpnomelane-albite-quartz
3) White mica-chlorite-epidote

} ± calcite

Basic schists

1) Chlorite-pumpellyite-albite 2) Chlorite-actinolite-albite 3) Chlorite-actinolite-pumpellyite-albite 4) Chlorite-actinolite-pumpellyite-epidote-albite 5) Chlorite-pumpellyite-epidote-albite	± white mica, stilpnomelane, calcite, quartz, sphene, opaque minerals

Among these, assemblage 3) is the most common in basic schists. Pumpellyite occurs commonly in association with stilpnomelane, while the pumpellyite-white mica association is rarely observed. Pumpellyite-glaucophane assemblage does not occur in this district. Metamorphic minerals in the basic rocks may have been produced by such reactions as shown below:

$$\underset{\text{anorthite}}{15CaAl_2Si_2O_8} + \underset{\text{clinopyroxene}}{11Ca(Mg, Fe)Si_2O_6} + 22H_2O$$
$$= \underset{\text{pumpellyite}}{6Ca_4Al_5(Mg, Fe)Si_6O_{23}(OH)_3 \cdot 2H_2O} + \underset{\text{actinolite}}{Ca_2(Mg, Fe)_5Si_8O_{22}(OH)_2}$$
$$+ \underset{\text{quartz}}{8SiO_2} \quad \cdots\cdots (2)$$

$$\underset{\text{chlorite}}{25(Mg, Fe)_5Al_2Si_3O_{10}(OH)_8} + \underset{\text{calcite}}{86CaCO_3} + \underset{\text{quartz}}{169SiO_2}$$
$$= \underset{\text{pumpellyite}}{10Ca_4Al_5(Mg, Fe)Si_6O_{23}(OH)_3 \cdot 2H_2O} + \underset{\text{actinolite}}{23Ca_2(Mg, Fe)_5Si_8O_{22}(OH)_2}$$
$$+ 86CO_2 + 42H_2O \quad \cdots\cdots (3)$$

The first equation represents a retrogressive reaction, whereas the second is a progressive one that defines the actinolite isograd in rocks of basic composition. Epidote

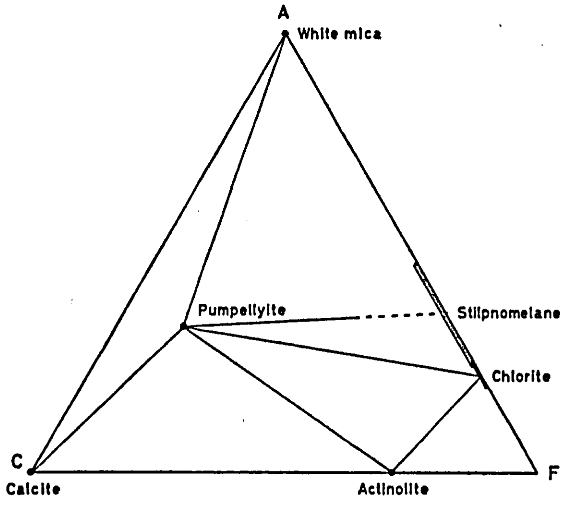


Fig. 9. ACF diagram for basic metamorphic rocks of zone B.

is rarely found in the higher grade part of zone B, in which the mineral occurs as very fine grains and is frequently associated with pumpellyite. In such case, the mineral may be considered to be an incipient phase of epidote that may be formed by the equation (4) or (4′), as will be given later.

The mineral assemblages for basic rocks of this zone may be represented in the ACF diagram of Fig. 9. These assemblages indicate that the metamorphic condition of zone B corresponds to that of a higher grade part of the prehnite-pumpellyite metagreywacke facies as defined by COOMBS (1960) or that of the pumpellyite-actinolite facies as defined by HASHIMOTO (1966).

E. METAMORPHIC ROCKS OF ZONE C

Metamorphic rocks of zone C are derived from pelitic, psammitic, basic and siliceous rocks. Recrystallization is far more advanced in this zone than in the preceding two zones and relic minerals have not been observed in any rocks of this zone.

Metamorphic minerals of zone C are quartz, albite, white mica, chlorite, calcite, stilpnomelane, epidote, actinolite, garnet and axinite in pelitic, psammitic and siliceous schists, and albite, calcite, white mica, chlorite, stilpnomelane, epidote, actinolite, subcalcic hornblende, glaucophane (normal symmetric) and axinite in basic schists. In zone C, pumpellyite disappears and epidote, glaucophane and subcalcic hornblende appear stably in basic schists.

The following mineral assemblages are observed in rocks of zone C:

Pelitic, psammitic and siliceous schists

1) White mica-chlorite-albite-quartz
2) White mica-chlorite-epidote-albite-quartz
3) White mica-chlorite-epidote-actinolite-albite-quartz
4) White mica-chlorite-garnet-albite-quartz
5) White mica-chlorite-epidote-garnet-albite-quartz
6) Chlorite-epidote-albite-quartz
7) Chlorite-epidote-garnet-albite-quartz
8) White mica-chlorite-epidote-axinite-albite-quartz
9) Chlorite-epidote-axinite-albite-quartz

(1–9) ± stilpnomelane, calcite, tourmaline, apatite, opaque minerals

Garnet occurs in pelitic and siliceous schists in the higher grade part of this zone, though biotite does not appear in any rocks of this zone. Actinolite occurs rarely in psammitic schists, while glaucophane has not been found in any siliceous schists. Axinite also occurs rarely in siliceous schists in the lower grade part of this zone.

Basic schists

1) Chlorite-epidote-albite
2) Chlorite-epidote-actinolite-albite
3) Chlorite-epidote-subcalcic hornblende-albite
4) Chlorite-epidote-subcalcic hornblende-actinolite-albite
5) Chlorite-epidote-glaucophane-albite

± white mica, stilpnomelane, calcite,

6) Chlorite-epidote-glaucophane-actinolite-albite
7) Chlorite-epidote-glaucophane (core)-subcalcic hornblende (rim)-albite
8) Chlorite-epidote-glaucophane (core)-actinolite (rim)-albite
9) Chlorite-epidote-axinite-albite

} quartz, sphene, opaque minerals

Epidote occurs stably in this zone, in which pumpellyite disappears, though it occurs rarely with pumpellyite in the higher grade part of zone B. This may be represented by the following reaction.

$$15\overset{\text{pumpellyite}}{Ca_4Al_5(Mg,\ Fe)Si_6O_{23}(OH)_3\cdot 2H_2O}+9\overset{\text{quartz}}{SiO_2}+4CO_2$$
$$=3\overset{\text{actinolite}}{Ca_2(Mg,\ Fe)_5Si_8O_{22}(OH)_2}+25\overset{\text{epidote}}{Ca_2Al_3Si_3O_{12}(OH)}$$
$$+4\overset{\text{calcite}}{CaCO_3}+37H_2O \quad \cdots\cdots (4)$$

or,

$$2\overset{\text{chlorite}}{(Mg,\ Fe)_7Al_4Si_4O_{15}(OH)_{12}}+41\overset{\text{pumpellyite}}{Ca_4Al_5(Mg,\ Fe)Si_6O_{23}(OH)_3\cdot 2H_2O}$$
$$+47\overset{\text{quartz}}{SiO_2}=11\overset{\text{actinolite}}{Ca_2(Mg,\ Fe)_5Si_8O_{22}(OH)_2}+71\overset{\text{epidote}}{Ca_2Al_3Si_3O_{12}(OH)}$$
$$+109H_2O \quad \cdots\cdots (4')$$

Glaucophane may be formed by the following reactions:

$$3\overset{\text{actinolite}}{Ca_2(Mg,\ Fe)_5Si_8O_{22}(OH)_2}+10\overset{\text{albite}}{NaAlSi_3O_8}+6CO_2+2H_2O$$
$$=5\overset{\text{glaucophane}}{Na_2(Mg,\ Fe)_3Al_2O_{22}Si_8(OH)_2}+6\overset{\text{calcite}}{CaCO_3}+14\overset{\text{quartz}}{SiO_2} \quad \cdots\cdots (5)$$

$$6\overset{\text{actinolite}}{Ca_2(Mg,\ Fe)_5Si_8O_{22}(OH)_2}+9\overset{\text{chlorite}}{(Mg,\ Fe)_5Al_2Si_3O_{10}(OH)_8}$$
$$+50\overset{\text{albite}}{NaAlSi_3O_8}=25\overset{\text{glaucophane}}{Na_2(Mg,\ Fe)_3Al_2O_{22}Si_8(OH)_2}$$
$$+6\overset{\text{epidote}}{Ca_2Al_3Si_3O_{12}(OH)}+7\overset{\text{quartz}}{SiO_2}+14H_2O \quad \cdots\cdots (6)$$

As to subcalcic hornblende, the discussion will be given in a later chapter.

Mineral assemblages for basic rocks of zone C may be shown in the ACF diagram as shown in Fig. 10. These assemblages, except for the presence of subcalcic hornblende, suggest that the metamorphic condition of zone C corresponds to the epidote-glaucophane subfacies defined by MIYASHIRO and SEKI (1958a).

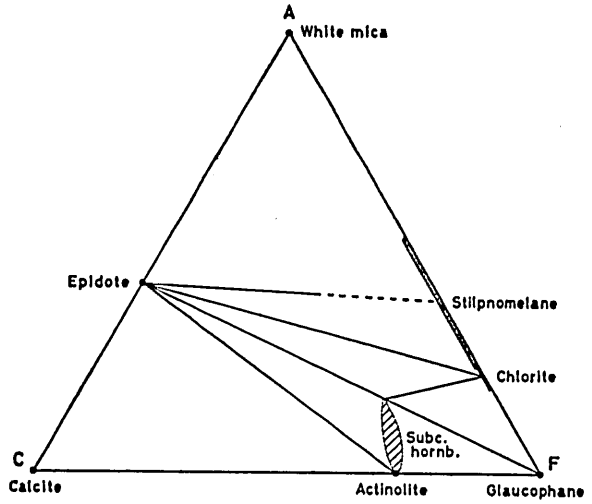


FIG. 10. ACF diagram for basic metamorphic rocks of zone C.

F. MINERALS OF METAMORPHIC ROCKS

In the Nishiki-chô district, the following minerals are found in ordinary pelitic, psammitic, siliceous and basic rocks; that is, quartz, plagioclase, white mica, chlorite, pumpellyite, epidote, piemontite, amphiboles (actinolite, subcalcic hornblende and crossite), stilpnomelane, garnet, calcite, sphene, axinite, tourmaline, apatite, oxide minerals (hematite and magnetite), sulfide minerals (pyrite, pyrrhotite and chalcopyrite) and carbonaceous matter. These minerals are so fine-grained and contain so many minute inclusions that it is difficult to separate from rocks sufficient amounts of pure minerals for detailed examinations.

Optical properties and X-ray diffraction data of some of these minerals are described in this section. Refractive indices of minerals were measured by the ordinary immersion method with the accuracy of ± 0.001. Optic axial angle 2V was measured on the five-axis universal stage by orthoscopic method. X-ray diffraction patterns were taken by the Geigerflex diffractometer under CuKα radiation.

1. *Plagioclase*

Plagioclase occurs as a common metamorphic mineral in every rocks of all the zones. Optical properties of some plagioclases from basic schists of zones B and C are as follows: $\alpha = 1.526$–1.530, $\gamma = 1.536$–1.540, $2V_Z = 75°$–$80°$. Plagioclases showing relic detrital features are found in rocks of zone A, and some of them from psammitic rocks have optic axial angles ($2V_Z$) ranging from 76°to 82°.

These data indicate that newly formed plagioclase through regional metamorphism is albite (An=0–5%), belonging to the low-temperature form in all parts of the Nishiki-chô district (CHAYES, 1952; SMITH, 1958).

Porphyroblastic plagioclase has not been found in this district.

2. *Chlorite*

Chlorite is the most common constituent minerals, and is present in almost all the metamorphic rocks of this district.

Basal spacing, refractive index β and optic sign of chlorites from psammitic and basic rocks of zone A to zone C were measured (Table 3 and Fig. 11). As shown in the table, all the examined chlorites are normal chlorites with (001) refraction of d=ca. 14 Å. NELSON and ROY (1958) suggested that septechlorite, having 7 Å structure, is a low temperature phase of normal chlorite with 14 Å structure, however, septechlorite could not be found even in rocks of zone B in the present district.

TABLE 3. BASAL SPACING AND OPTICAL PROPERTIES OF CHLORITES AND $Fe^{+2}/(Mg+Fe^{+2})$ RATIO OF HOST ROCKS

Zone	Spec. No.	Chlorite			Host Rock
		d (001) Å	β	±	$Fe^{+2}/(Mg+Fe^{+2})$
B	391031-1	14. 20	1. 630	−	0. 49
B	6656-4	14. 20	1. 654	−	0. 76
C	189-32	14. 11	1. 620	+	0. 36
C	6656-8	14. 18	1. 617	+	0. 38
C	661019-4	14. 20	1. 623	+	0. 41
C	6655-17	14. 13	1. 630	−	0. 45
C	189-11	14. 15	1. 641	−	0. 60
C	189-8	14. 13	1. 656	−	0. 77

Fig. 11 shows that the refractive index β of chlorites varies from 1.616 to 1.657, and the birefringence $(\gamma-\alpha)$ ranges from 0.000 to 0.006. Chlorites with β lower than 1.627 and abnormal brown interference color show positive optic sign, whereas those with β higher than 1.629 and abnormal blue or violet interference color show negative optic sign. Chlorites with β ranging from 1.627 to 1.629 show either positive or negative optic sign and the two kinds of chlorites, in some cases, coexist in one and the same thin section. These optical properties are well in harmony with the view of ALBEE (1962).

The probable composition field of these chlorites can be shown by the method of SHIROZU (1960a) in Fig. 12. As seen from the figure, chlorites from the Nishiki-chô district belong to both ripidorite and aphrosiderite after the nomenclature of WINCHELL and WINCHELL (1951). The figure also illustrates that the composition range of chlorites is large in regard to Mg↔Fe substitution and is rather small in (Mg+Fe) Si↔AlAl substitution, as already suggested by SHIROZU (1960b) and BANNO (1964). Therefore, the refractive index β of chlorite may be regarded as a good parameter of Fe^{+2} content of chlorite.

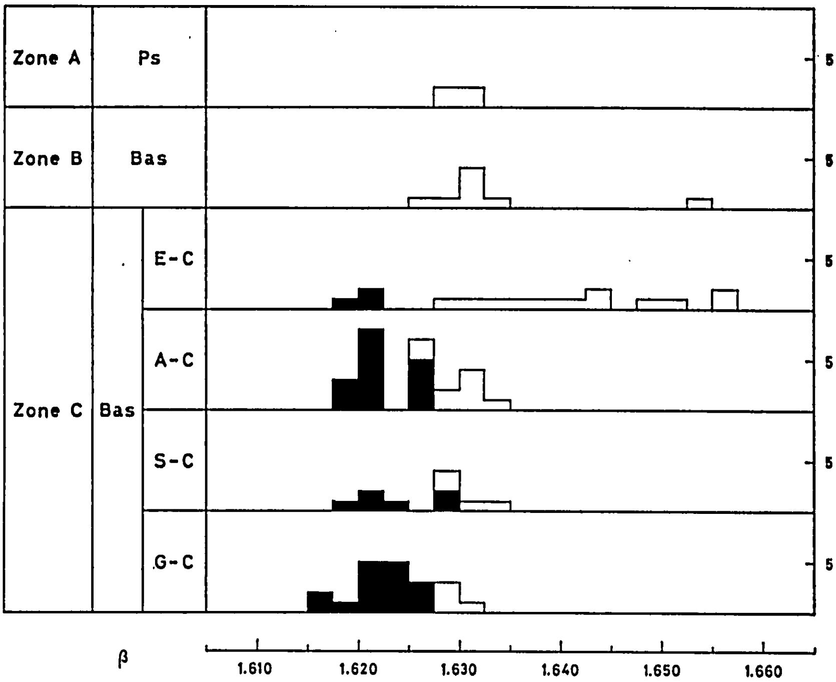


FIG. 11. Frequency distribution of refractive index β for chlorites. White and black areas show the negative and the positive varieties, respectively. Abbreviations are represented as follows: Ps=psammitic rocks, Bas=basic schists, E-C=epidote-chlorite assemblage, A-C=actinolite-epidote-chlorite assemblage, S-C=subcalcic hornblende-epidote-chlorite assemblage, G-C=glaucophane-epidote-chlorite assemblage.

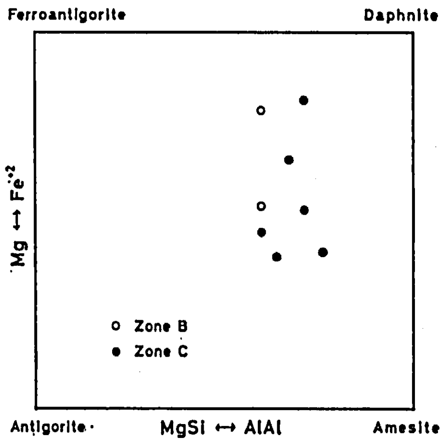


FIG. 12. Composition of chlorites estimated from the optical properties and (001)-spacings (after SHIROZU, 1960a).

It has been presumed, on one hand, that the FeO content of chlorites in basic schists increases with increasing grade of metamorphism (IWASAKI, 1963; BANNO, 1964) and, on the other hand, that it is mainly governed by the $Fe^{+2}/(Mg+Fe^{+2})$ ratio of host rocks (MIYASHIRO, 1957a, 1958; KANISAWA, 1964; KANEHIRA, 1967). The $Fe^{+2}/(Mg+Fe^{+2})$ ratio of host rocks and the refractive index β of chlorites are plotted on a rectangular diagram (Fig. 13). The diagram shows that the refrac-

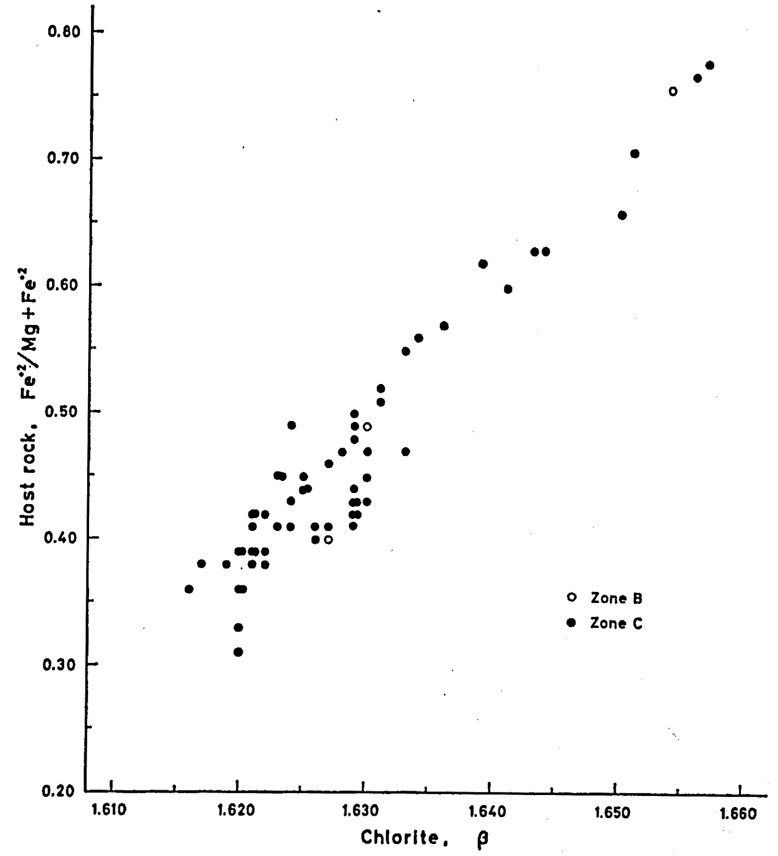


FIG. 13. Relation between $Fe^{+2}/(Mg+Fe^{+2})$ ratio of host rocks and refractive index β of chlorites in basic schists.

tive index β, which can be estimated to represent the Fe^{+2} content, of chlorites is distinctly correlated with the $Fe^{+2}/(Mg+Fe^{+2})$ ratios of host rocks. Moreover, range of the refractive index β of chlorites shows no significant difference from zone to zone, as shown in Fig. 11.

The refractive index β of chlorites associated with amphiboles is lower than 1.633, while that of chlorites not associated with amphiboles is mainly higher (Fig. 11). Close relationship between the refractive index of chlorite and that of the associated amphiboles will be mentioned later.

It is commonly observed that chlorites in glaucophane schists are deeper in green color than those in glaucophane-free schists of the same zone. HORIKOSHI (1965) clarified that the deep green-color of chlorite is related to its Fe_2O_3 content, and also Fe_2O_3 content of chlorite is mainly related to that of the host rocks. These facts are in harmony with the view that the formation of glaucophane schists is due to higher Fe_2O_3/FeO ratio of the host rocks than that of glaucophane-free schists, as will be mentioned later.

3. *Pumpellyite*

Pumpellyite is the most important metamorphic mineral, occurring widely in basic and psammitic rocks of zone A and in basic schists of zone B. Both colorless and green varieties are observed in the Nishiki-chô district. The former occurs generally as very fine tabular crystals in detrital plagioclase and as segregation veins in psammitic rocks of zone A, whereas the latter occurs commonly as idiomorphic needle-like or tabular crystals not only in matrix but also in lenticular pools and segregation veins in basic schists of zone B.

Precise determination of optical properties of pumpellyite is somewhate difficult either due to very fine-grain size or to strong dispersion of the mineral.

Pumpellyite may be stably associated with quartz, albite, calcite, chlorite, white mica, stilpnomelane and actinolite, but may be metastable in association with epidote. Such assemblages as prehnite-pumpellyite, pumpellyite-lawsonite and pumpellyite-glaucophane have not been observed in any rocks of this district.

4. *Epidote*

Epidote is a chief constituent of basic schists of zone C, while rare in basic schists of zone B. The mineral is also found in pelitic and psammitic schists of zone C. Epidote in basic schists was mainly examined.

Epidote begins to occur in basic schists of the highest grade part of zone B, in which the mineral is only locally found as very fine grains and generally associated with pumpellyite. In zone C, in which pumpellyite disappears, epidote becomes the most common metamorphic mineral being associated stably with either actinolite, subcalcic hornblende or crossite, but with no pumpellyite, in basic schists. The mineral occurs commonly as xenomorphic large crystals and sometimes shows weak zonal structure. Epidote may have been formed from pumpellyite, as represented by the equation (4) or (4′) in the preceding section. In such case, epidote occurring in zone B may be considered to represent the most incipient stable phase.

After MIYASHIRO and SEKI (1958b), epidote having compositions near $HCa_2Al_2FeSi_3O_{13}$ (that is, Al: Fe=2: 1, or 33 molecular percent Fe^{+3} end-member) is most stable at very low temperature, and the composition field of epidote enlarges toward higher and lower Fe^{+3} contents with increasing grade of metamorphism. The range of $2V_X$ of epidotes from basic schists of the Nishiki-chô district is shown

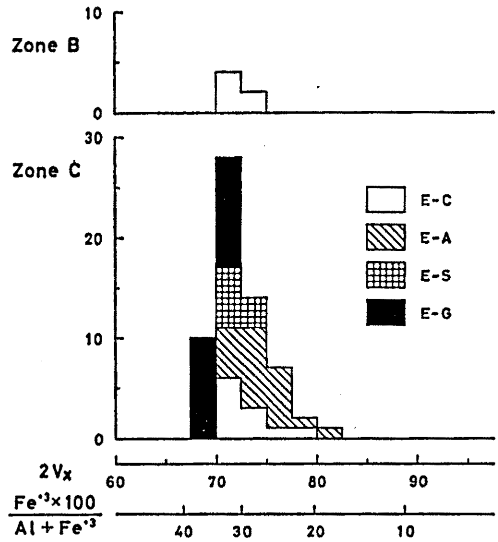


FIG. 14. Frequency distribution of optical angle for epidotes from basic schists of zones B and C. The $Fe^{+3}/(Al+Fe^{+3})$ ratio corresponding to optical angle was taken from WINCHELL and WINCHELL's diagram (1951). Abbreviations are identical with those of Fig. 11.

in Fig. 14. As seen in the figure, $2V_X$ for epidotes of zone B ranges from 70° to 74°, whereas that of zone C ranges from 68° to 82°. The range of $2V_X$ shows the tendency to enlarge from zone B to zone C, though available data are insufficient in zone B. Moreover, it is noteworthy that the incipient epidote of zone B at lower temperature shows narrower composition field near 33 molecular percent Fe^{+3} end-member. It is also interesting that the range of $2V_X$ of epidotes in zone C is similar to that of lower grade parts in other glaucophanitic metamorphic terrains of Japan, that is, the zone of weakly metamorphosed Paleozoic rocks of the Kanto Mountains (MIYASHIRO and SEKI, 1958b), zones I and II of the Sibukawa district (SEKI, AIBA and KATO, 1959), zone II of the Kôtu–Bizan area (IWASAKI, 1963) and the low-grade metamorphic rocks of the Kitakami Mountainland (KANISAWA, 1964).

As shown in Fig. 14, epidotes in glaucophane schists have smaller optical angles than those in glaucophane-free schists. This fact is in harmony with the view that glaucophane forms commonly in Fe_2O_3-rich rocks, as will be shown in the later chapter.

Piemontite occurs rarely in siliceous schists of zone C on the south of this district (KINOSHITA and TAKEHARA, 1936).

5. *Amphiboles*

Amphiboles are important constituents of basic schists. In the Nishiki-chô district, three kinds of amphiboles can be discriminated on preliminary optical examination.

The minerals, however, are so fine-grained, including so many minute inclusions, that the author cannot so far obtained a sufficient amount of pure material for the chemical examination. Therefore, amphiboles in question are classified on the basis of optical properties into three varieties, namely, actinolite, subcalcic hornblende and crossite. Optical properties of them are summarized in Table 4.

TABLE 4. OPTICAL PROPERTIES OF AMPHIBOLES

	Actinolite	Subcalcic hornblende	Crossite
α	1.626-1.638	1.633-1.641	1.643-1.654
β	1.641-1.655	1.652-1.660	1.659-1.671
γ	1.651-1.662	1.660-1.667	1.665-1.676
$2V_X$	63°-75°	43°-60°	34°-76°
$c \wedge Z$	16°-18°	17°-21°	(b=Z)
X	colorless	colorless	pale yellow
Y	very pale green	pale green	bluish green
Z	very pale green	bluish green	bluish violet

Actinolite occurs as acicular crystals commonly in basic schists of zones B and C, and rarely in psammitic schists of zone C. This mineral can be distinguished from other two varieties by the axial color for Z of very pale-green, the low refractive index and the large optic axial angle. This belongs to actinolite proper in ordinary sense. Bluish green hornblendes, which show characteristic axial color for Z of bluish green and smaller optic axial angles than actinolite proper, occur as subhedral to unhedral tabular crystals in basic schists of zone C. These are tentatively called subcalcic hornblende in this paper. Optic axial angle $2V_X$ and refractive index γ of the subcalcic hornblendes are plotted together with those of hitherto analyzed ones in Fig. 15. Judging from these optical properties, the minerals may correspond to such varieties as bluish green actinolite (SEKI, 1958), glaucophanic actinolite and barroisite (IWASAKI, 1963), and subcalcic hornblende (BANNO, 1964), which are intermediate in composition between calcium amphiboles and alkali amphiboles.

Alkali amphiboles, showing characteristic axial color for Z of bluish violet, occur only in basic schists of zone C. These usually occur as isolated subhedral to unhedral crystals, but sometimes coexist either with actinolite or subcalcic hornblende. Observed alkali amphiboles are all normal symmetric ones. In Fig. 16, optic axial angle $2V_X$ and refractive index γ of the alkali amphiboles are plotted together with those of hitherto analyzed ones. From the figure and Table 4, alkali amphiboles in this district are subglaucophane or crossite as defined by MIYASHIRO (1957b).

Three kinds of amphiboles occur separately, in general, in the rocks of zone C. In some rocks, however, both actinolite and crossite are observed as separate grains on the same thin section. Optical properties of coexisting actinolite and crossite are shown in Table 5 (see also Fig. 17). Similar associations of calciferous and alkali

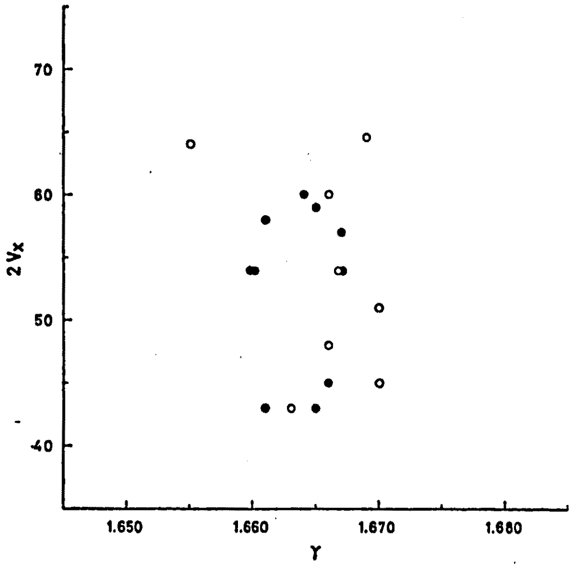


Fig. 15. 2V-γ diagram for subcalcic hornblendes.
Solid circles: Subcalcic hornblendes from the Nishiki-chô district.
Open circles: Analyzed subcalcic hornblendes from the various metamorphic terrains (after Seki, 1958; Iwasaki, 1963; Banno, 1964; Kanehira, 1967; Hashimoto, 1968a).

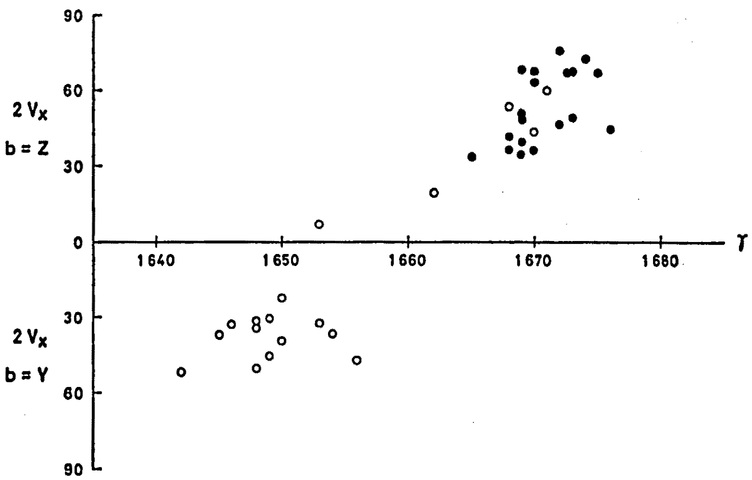


Fig. 16. 2V-γ diagram for alkali amphiboles.
Solid circles: Alkali amphiboles from the Nishiki-chô district.
Open circles: Analyzed alkali amphiboles from the various metamorphic terrains (after Seki, 1958; Iwasaki, 1963; Banno, 1958, 1964; Hashimoto, 1968a; Coleman and Papike, 1968).

TABLE 5. OPTICAL PROPERTIES OF COEXISTING ACTINOLITE AND CROSSITE

Spec. No.	38513-6		6657-1		189-20	
	actinolite	crossite	actinolite	crossite	actinolite	crossite
α	1.631	1.645	1.633	1.643	—	—
β	1.654	1.671	1.653	1.663	—	—
γ	1.661	1.673	1.661	1.668	1.658	1.675
$2V_X$	66°	49°	63°	37°	67°	48°
Z	very pale green	pale bluish violet	very pale green	greenish violet	very pale bluish green	bluish violet

amphiboles were described in other glaucophanitic metamorphic terrains. The relation was interpreted to represent coexisting equilibrium phases, and the extent of compositional gap between calciferous and alkali amphiboles was shown by IWASAKI (1963), BANNO (1964), LEE et al. (1966), HIMMELSBERG and PAPIKE (1969) and KLEIN (1969). Zoned amphiboles consisting of the core of crossite and the rim of actinolite or subcalcic hornblende are also common in basic schists of zone C. Reverse relation with peripheral alkali amphibole around calcic core has not been observed in the present study.

It was assumed by MIYASHIRO (1968) that actinolite is not associated with subcalcic hornblende in any rocks and that compositional variation from actinolite to subcalcic hornblende with increasing temperature appears to be continuous. In the Nishiki-chô district, however, two kinds of calciferous amphiboles, namely actinolite and subcalcic hornblende, are observed separate grains on the same thin section. Optical properties of coexisting actinolite and subcalcic hornblende are shown in Table 6 (see also Fig. 17). This fact demonstrates that actinolite can be associated stably with subcalcic hornblende under a certain condition. This problem will be considered in the later chapter.

Optical data of amphiboles, as described above, are plotted on the $(2V-\gamma)$ relation diagram (Fig 17). These three kinds of amphiboles are distinctly divided into three separate fields, respectively. Tie-lines in the figure represent the coexisting relation of the two amphiboles as mentioned above. The variation trend of calciferous

TABLE 6. OPTICAL PROPERTIES OF COEXISTING ACTINOLITE AND SUBCALCIC HORNBLENDE

Spec. No.	391011-1		661019-4	
	actinolite	subcalcic hornblende	actinolite	subcalcic hornblende
α	—	—	—	1.633
β	—	—	—	1.652
γ	1.658	1.665	—	1.660
$2V_X$	69°	59°	63°	54°
Z	very pale green	pale bluish green	very pale green	pale bluish green

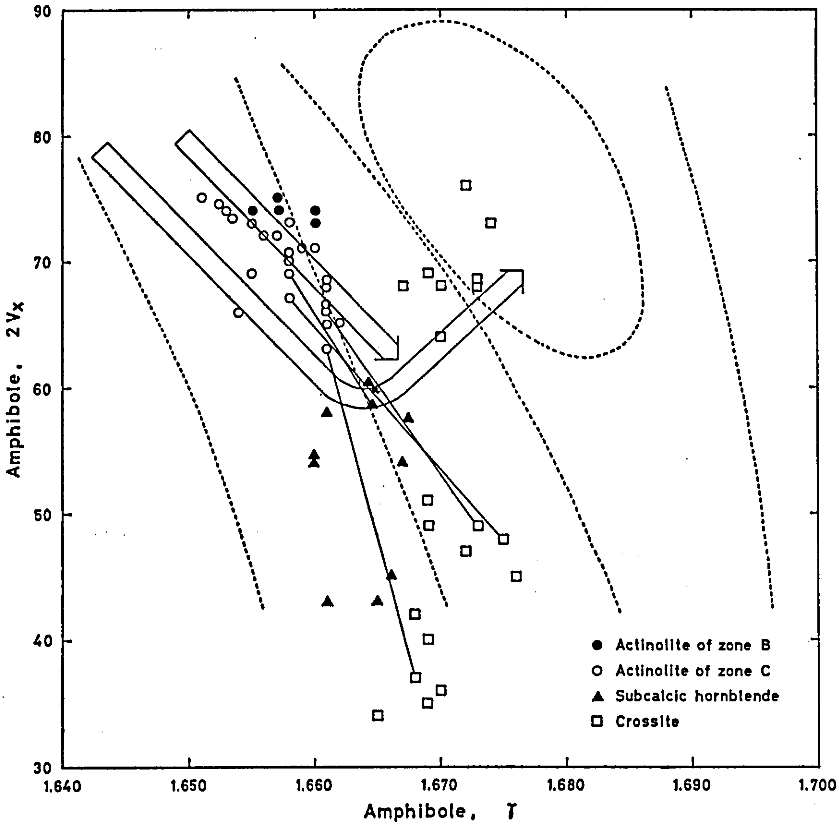


FIG. 17. 2V-γ relations for actinolite, subcalcic hornblende and crossite from the Nishiki-chô district.
Tie-lines indicate the coexisting relation of the two amphiboles. Dotted lines and arrows are quoted from MIYASHIRO (1968).

amphiboles of the present district is different from those of the Kanto Mountains, the Bessi–Ino district and the Shirataki district in Sambagawa metamorphic belt (MIYASHIRO, 1968; ERNST et al., 1970).

Refractive indices of amphiboles and the associated chlorites from basic schists of zones B and C are plotted on a rectangular diagram (Fig. 18). In the figure, distribution field of three kinds of amphiboles, namely, actinolite, subcalcic hornblende and crossite, is distinctly separated from each other, and the refractive index γ of amphiboles varies sympathetically to the refractive index β of the associated chlorites. The sympathetic variation trend in refractive indices of coexistent amphiboles and chlorites can be regarded as mainly related to $Fe^{+2}/(Mg+Fe^{+2})$ ratio of host rocks. That is, the higher $Fe^{+2}/(Mg+Fe^{+2})$ ratio of host rock, the higher the refractive index of the minerals (Fig. 18). With regard to coexisting actinolite and chlorite, similar relation was described by some authors (MIYASHIRO, 1958;

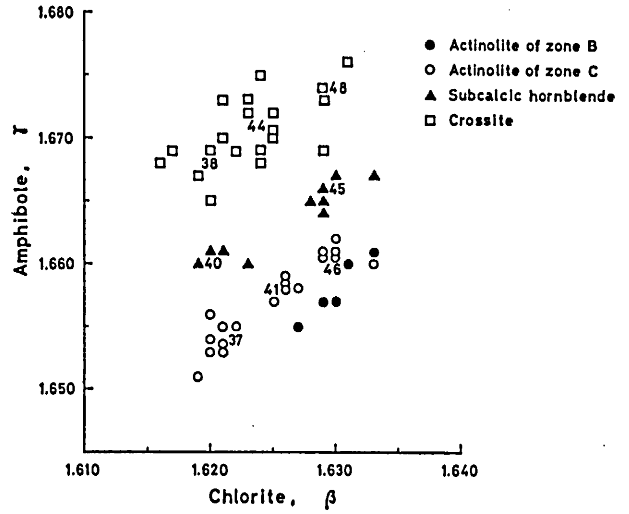


FIG. 18. Relation between refractive index γ of amphiboles and index β of the associated chlorite in basic schists.
Numbers represent the average $Fe^{+2} \times 100/(Mg+Fe^{+2})$ ratios of the host rocks.

KANISAWA, 1964).

MIYASHIRO (1958) and HASHIMOTO (1968a) stated that no relationship between the refractive indices of actinolite and metamorphic grade was found. In the Nishiki-chô district, however, refractive indices of actinolite in zone B are lower than those in zone C with respect to the same refractive index β of the associated chlorite. That may be related to the disappearance of iron-rich pumpellyite in basic schists of zone C. KANEHIRA (1967) also showed that refractive indices of calciferous amphiboles (actinolite and subcalcic hornblende) against those of associated chlorite increase with increasing grade of metamorphism in the Iimori district in the Sambagawa metamorphic belt.

6. *Stilpnomelane*

Stilpnomelane has been found commonly in various rocks through all zones. It is notable that the mineral occurs stably in the higher grade part of zone A. Refractive indices β of stilpnomelane in various zones are shown in Fig. 19. The color on the maximum absorption axis varies from pale green to deep reddish-brown.

In a basic schist, of which the surface part is weathered within a few centimeters, axial color of stilpnomelane varies from pale green through olive brown to reddish brown with increasing weathering of the host rock. Refractive index β of fresh stilpnomelane is 1.589, whereas in a strongly weathered part it is 1.688. Judging from these data, some of ferric stilpnomelanes may be due to later oxidation of ferrous component, as has been suggested by HUTTON (1938), ZEN (1960) and

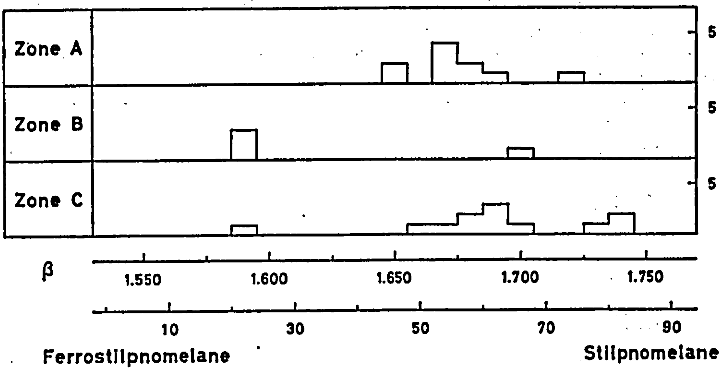


FIG. 19. Frequency distribution of refractive index β for stilpnomelanes. The compositional scale corresponding to refractive index is quoted from DEER et al. (1962).

BROWN (1967).

7. *Sulfide and oxide minerals*

Opaque minerals occur usually as minor constituents in metamorphic rocks of this district. Rocks corresponding to zones A and B contain smaller amounts of the minerals than one percent by volume. In zone C, the amount of the minerals varies greatly, ranging up to 3 percent by volume. Sulfide and oxide minerals in basic schists of zones B and C are preliminarily investigated. The minerals were identified under the ore microscope by courtesy of Dr. S. TAKENO. Data on the occurrence of sulfide and oxide minerals in the schists are shown in Table 7. Sulfide minerals consist of pyrrhotite, pyrite, marcasite and chalcopyrite. Oxide minerals include magnetite and hematite. Ilmenite has not been found in any rocks of this district.

Pyrrhotite occurs sporadically as minute grains in almost all of basic schists of zones B and C. This mineral occasionally coexists with pyrite forming separate grains on one and the same polished specimen. Some pyrrhotites rarely replace a part of hematite. Pyrite occurs rarely in basic schists of zone B, while in zone C the mineral is fairly common in glaucophane-free schists but uncommon in glaucophane schists. Pyrite is often observed to be replaced partially by marcasite, presumably in fairly later stages. Chalcopyrite is very rare. Pyrrhotite and pyrite cannot be assumed to be formed at a certain stage of mineralization but would have grown through at least a few different stages.

Magnetite occurs as euhedral to subhedral crystals in basic schists of zone C, specifically distinct in glaucophane schists. Magnetite is generally replaced by hematite along the marginal part or within any part of the grain. The mineral not replaced by hematite is also found. Sometimes, magnetite is associated with euhedral to subhedral hematite, which may be considered to be a stable coexisting phase. Magnetite-hematite intergrowth, consisting of magnetite host and hematite lamellae, has also been observed rarely. Hematite is common in basic schists of zone C.

TABLE 7. MINERAL ASSEMBLAGES OF SULFIDE AND OXIDE MINERALS IN BASIC SCHISTS OF THE NISHIKI-CHÔ DISTRICT

Zone	Min. Ass.	Spec. No.	Po	Py	Cp	Mc	Mg	Hm	Comments
B		65816-3	•						
		6656-2	•	•					euhedral-subhedral Py
		6656-4	•						
		661022-6	•						
		661022-8	•						
		69312-5	•	•					
		69318-1	•						
		69326-1	•						
		69326-10	•						
C	E-C	38729-11	•	•					
		381225-1		△					
		6655-2	•				•	△	Mg→Hm→Po
		6655-18	•						
		6656-5	•	•					
		6657-3					•	△	euhedral-subhedral Hm, Mg→Hm
		189-10					◎		
		189-31						○	subhedral Hm
	A-C	38730-1		△				○	subhedral-anhedral Hm
		3885-7		△		•			Py→Mc
		6655-7	•	•					
		6655-11	•					△	
		6655-13	•	△					subhedral Py
		6656-16	•	△	•				
		6656-17		•				△	euhedral-subhedral Hm
	S-C	391011-1	•	○		•			
		6655-9	•	•					
		6655-15	•				○	○	Mg→Hm
		6655-17						○	euhedral-subhedral Hm
		6657-2			•	△	○		
	G-C	38520-5	•				○	○	Mg→Hm
		38513-6	•				◎	○	Mg→Hm, Mg-Hm intergrowth
		38729-1					◎	○	Mg→Hm
		3886-5				•	◎	◎	Mg→Hm, Py→Mc
		6655-4					○	○	euhedral Hm
		6655-12	•				○		
		6656-8					○	◎	Mg→Hm
		6656-9	•				○	○	Mg→Hm
		6656-10					◎	◎	euhedral Hm, Mg→Hm
		6657-1					◎		
		189-15	•				○		
		189-27	•				○	○	Mg→Hm
		189-30					◎		

E-C = epidote-chlorite assemblage A-C = actinolite-epidote-chlorite assemblage
S-C = subcalcic hornblende-epidote-chlorite assemblage G-C = glaucophane-epidote-chlorite assemblage
Po = pyrrhotite Py = pyrite Cp = chalcopyrite Mc = marcasite Hm = hematite Mg = magnetite
• = very rare △ = rare ○ = common ◎ = abundant → = replaced by

Euhedral to subhedral hematite, which does not occur replacing magnetite, does not coexist with pyrrhotite, while hematite replacing magnetite is associated with pyrrhotite. HOLLAND (1959) and KANEHIRA et al. (1964) showed that pyrrhotite is incompatible with hematite in any sulfur and oxygen pressures at low temperature. Therefore, it may be inferred that some of hematites were formed at a certain stage of regional metamorphism different from the main stage of mineralization.

It is summarized that the mineral or the mineral assemblage of sulfides and oxides in zone B is either pyrrhotite or pyrite-pyrrhotite, whereas those in zone C are as follows: pyrrhotite, pyrite, magnetite, hematite, pyrite-pyrrhotite, magnetite-pyrrhotite, magnetite-hematite and pyrite-hematite. BANNO and KANEHIRA (1961) and KANEHIRA et al. (1964) showed that in glaucophanitic metamorphic terrains such as the districts of Bessi, Iimori, Kôtu and Ômi in Japan, the assemblage pyrite-hematite is common and magnetite is very rare in basic schists. However, in the Nishiki-chô district, belonging to the glaucophanitic metamorphic terrain in a broad sense too, the assemblage pyrite-hematite is rather rare and magnetite often occurs in basic schists. Magnetite appears to be nearly as common as hematite also in glaucophane schists of the California Central Coast Ranges (ERNST, 1962).

In the Nishiki-chô district, moreover, it may be worthy of note that glaucophane schists contain either magnetite or magnetite-hematite, while glaucophane-free schists include pyrite and/or hematite (Table 7). This fact seems to be incompatible with the view that high oxygen pressure favors the formation of crossite, as will be mentioned later. The reason of this respect has not yet been solved.

8. *Other minerals*

Garnet occurs in pelitic and siliceous schists of the higher grade part of zone C, whereas biotite does not appear in any rocks of this zone. Detailed physical and chemical properties of the garnet have not been clarified. HASHIMOTO (1968a) emphasized that in glaucophanitic metamorphic terrain, the garnet isograd in rocks of pelitic composition is located on the lower temperature side of the biotite isograd in rocks of similar composition.

Axinite was found in siliceous and basic schists of the lower grade part of zone C. NUREKI (1967) described the mineral and discussed genetically.

Minerals or mineral assemblages such as jadeite-quartz and aragonite, which demonstrate higher pressure metamorphic condition, have not been found in any rocks not only of the Nishiki-chô district but also throughout the whole Sangun metamorphic belt. Lawsonite, which is also generally regarded as a typical mineral of higher pressure metamorphism, also has not been detected in the present district. Recently, however, some rare occurrences of the mineral have been reported from the Sangun metamorphic belt (HASHIMOTO and IGI, 1970).

IV. PETROCHEMISTRY OF BASIC METAMORPHIC ROCKS

It is becoming clear that kind and intensity of magmatism in the metamorphic belt vary with the type of metamorphism. The glaucophanitic metamorphic belt is accompanied by abundant ophiolitic rocks but is devoid of granitic ones, whereas the non-glaucophanitic belt is accompanied by a great amount of granitic rocks but is poor of ophiolitic ones (MIYASHIRO, 1967, 1968). On the other hand, mineral assemblage as well as metamorphic reaction depend critically on the bulk composition of rocks. Therefore, it is important to know the bulk composition of basic metamorphic rocks in order to clarify the nature of glaucophanitic metamorphism. Seventy-five basic metamorphic rocks from the Tsuno Group were chemically analyzed for this purpose. The results are listed in Tables 8 and 9. Brief petrographic descriptions and the locality of analyzed rocks are also given in the appendix.

A. CHEMICAL COMPOSITION AND ORIGIN OF BASIC METAMORPHIC ROCKS

Chemical composition and origin of basic metamorphic rocks in the Nishiki-chô district were discussed in some detail by NISHIMURA (1971). The following is a brief outline of the paper with some newly obtained data.

Basic metamorphic rocks in question occur specifically in the upper formation of the Tsuno Group, and occur scarcely in its lower formation and in the Nishiki Group (see Fig. 3 and Plate XV) Basic metamorphic rocks occurring in the uppermost horizon (Tu-6) form generally very thin layers, which vary in thickness from several centimeters to a few meters, whereas those in the other lower horizons (Tu-2 and Tu-4) form relatively larger masses of lenticular or amoeboid shapes with the thickness of about 250 m. Mode of occurrence and nature of the basic metamorphic rocks on the field suggest that the basic rock masses in question would have been derived from sills or lacoliths intruded concordantly or subconcordantly into water-saturated pelites in the geosynclinal phase.

The basic sills have specified petrographical and petrochemical features in common. That is, the main part of the masses, consisting of coarse-grained green rocks showing normal gabbroic composition (type I), is bordered by pale-green, slightly schistose, fine-grained rocks (type II), which are fairly different in composition and fabrics from the main part of the body.

Petrochemical nature of the peripheral zone (type II) is clearly illustrated in the $(MgO+CaO)$-$(Al_2O_3+K_2O)$ diagram, in which type I and type II rocks are represented by solid and open circles, respectively (Fig. 20). Points linked by tie-lines with arrows represent the specimens selected from a drill core of a basic schist mass, about 25 m thick, which intervened between two pelitic schist beds. The arrows represent the order from the upper to the lower horizon. The cross mark on the diagram represents the average composition of 31 Paleozoic pelites from the

TABLE 8. CHEMICAL COMPOSITIONS OF BASIC SCHISTS COLLECTED ON THE FIELD

ANALYST: Y. NISHIMURA

No.	1	2*	3	4	5*	6*	7	8
SiO_2	48.79	48.55	48.99	52.27	46.35	52.42	50.32	47.42
Al_2O_3	13.99	13.60	16.60	16.97	14.14	13.15	16.19	12.78
Fe_2O_3	1.18	0.92	0.77	1.01	1.84	1.33	0.87	2.86
FeO	11.37	11.02	12.61	10.00	10.55	9.08	12.09	8.37
MgO	6.63	6.70	4.63	1.80	8.70	5.03	3.95	6.25
CaO	5.10	10.15	1.72	3.74	7.59	8.16	1.24	7.88
Na_2O	4.32	3.04	2.89	5.58	3.03	4.12	0.27	1.80
K_2O	0.36	0.44	1.47	1.10	0.57	0.59	3.98	0.77
TiO_2	2.25	1.07	1.79	2.88	1.65	1.77	1.78	1.96
P_2O_5	0.18	0.22	0.18	0.59	0.23	0.51	0.18	0.14
MnO	0.21	0.12	0.29	0.35	0.12	0.11	0.45	0.29
H_2O+	4.42	4.16	6.67	3.71	4.96	3.41	7.22	9.37
H_2O-	0.56	0.10	1.09	0.33	0.02	0.08	1.36	0.52
Total	99.36	100.09	99.70	100.33	99.75	99.76	99.90	100.41

TABLE 8. (Continued)

No.	9	10	11	12	13	14	15	16
SiO_2	46.66	50.15	49.55	47.25	45.24	42.95	48.92	47.41
Al_2O_3	14.27	13.04	13.25	13.95	14.82	14.70	13.64	13.64
Fe_2O_3	5.62	5.79	6.04	7.32	5.98	3.26	4.63	6.69
FeO	8.54	7.07	5.85	7.32	6.50	7.34	6.81	8.35
MgO	6.68	6.40	6.54	5.06	5.88	5.04	6.26	4.98
CaO	8.29	7.24	9.04	7.71	8.96	11.53	9.12	7.56
Na_2O	3.16	4.15	4.16	3.67	3.14	2.67	2.88	3.41
K_2O	0.93	0.75	0.79	0.62	0.50	1.02	0.43	1.03
TiO_2	0.95	1.92	1.20	2.03	0.56	0.62	1.93	0.96
P_2O_5	0.18	0.12	0.17	0.13	0.13	0.16	0.22	0.23
MnO	0.30	0.05	0.23	0.21	0.32	0.25	0.17	0.19
H_2O+	4.03	3.42	3.02	3.87	7.40	9.66	4.14	4.70
H_2O-	0.39	0.43	0.21	0.51	0.56	0.49	0.36	0.45
Total	100.00	100.53	100.05	99.65	99.99	99.69	99.51	99.60

Table 8. (Continued)

No.	17	18	19	20	21	22	23	24
SiO_2	48.34	46.79	45.73	36.97	48.91	49.73	50.22	46.02
Al_2O_3	13.56	19.20	13.04	17.99	12.89	13.48	16.29	13.68
Fe_2O_3	3.39	5.55	2.35	1.62	6.91	6.31	6.62	2.57
FeO	9.34	4.75	8.83	17.57	6.15	6.56	4.47	10.42
MgO	6.46	4.29	6.79	6.04	4.99	4.63	3.58	8.29
CaO	7.71	9.32	8.18	4.13	11.24	9.85	8.78	8.36
Na_2O	3.96	3.35	2.97	2.36	1.88	2.80	3.74	2.74
K_2O	0.23	0.90	0.23	0.36	0.30	0.53	0.35	0.24
TiO_2	2.54	1.18	1.67	2.96	1.51	2.14	1.38	2.25
P_2O_5	0.14	0.32	0.10	0.10	0.15	0.28	0.17	0.19
MnO	0.23	0.13	0.22	0.29	0.37	0.24	0.20	0.21
H_2O+	3.74	3.36	8.41	8.08	3.96	2.97	3.64	4.56
H_2O-	0.33	0.34	0.75	0.73	0.29	0.31	0.27	0.34
Total	99.97	99.48	99.27	99.20	99.55	99.83	99.71	99.87

Table 8. (Continued)

No.	25	26	27	28	29	30	31	32
SiO_2	44.01	50.17	47.50	45.28	47.65	45.94	49.40	46.65
Al_2O_3	12.45	14.02	13.89	14.65	13.64	13.58	13.03	13.57
Fe_2O_3	3.43	10.16	6.17	2.45	3.16	2.80	2.48	4.33
FeO	7.88	4.49	6.88	9.33	8.41	10.28	9.81	8.82
MgO	5.76	4.34	3.82	8.26	6.27	6.78	6.28	7.07
CaO	13.21	5.76	9.68	10.18	10.01	8.30	8.66	11.11
Na_2O	2.32	3.75	4.44	1.72	3.19	2.71	2.64	2.21
KO_2	0.26	1.00	0.33	0.55	0.45	0.11	0.27	0.42
TiO_2	1.61	1.70	2.22	1.70	2.33	2.28	1.24	0.46
P_2O_5	0.14	0.14	0.22	0.15	0.19	0.19	0.20	0.12
MnO	0.22	0.24	0.22	0.21	0.13	0.44	0.22	0.23
H_2O+	7.76	3.36	4.06	4.84	3.97	5.69	5.11	4.20
H_2O-	0.38	0.34	0.41	0.62	0.48	0.75	0.81	0.43
Total	99.43	99.47	99.84	99.94	99.88	99.85	100.15	99.62

TABLE 8. (Continued)

No.	33	34	35	36	37	38	39	40
SiO_2	43.19	44.41	46.27	48.40	48.77	47.99	47.17	48.57
Al_2O_3	19.13	16.08	15.38	12.98	13.83	14.09	13.06	12.75
Fe_2O_3	1.62	4.98	9.72	5.77	6.80	3.33	2.86	2.58
FeO	14.00	8.00	5.24	7.90	7.96	8.05	9.19	9.59
MgO	4.72	6.93	4.84	5.57	5.41	7.18	8.20	7.57
CaO	2.65	7.34	5.72	8.89	6.41	10.54	10.31	7.77
Na_2O	3.32	2.49	2.97	2.41	4.51	2.61	2.23	3.31
K_2O	2.53	0.46	1.72	0.63	0.90	0.24	0.21	1.01
TiO_2	2.50	3.28	2.04	0.98	2.14	1.44	1.45	1.81
P_2O_5	0.19	0.49	0.19	0.14	0.08	0.14	0.16	0.13
MnO	0.36	0.14	0.10	0.28	0.15	0.19	0.18	0.19
H_2O+	6.04	5.26	5.01	5.33	3.44	3.47	4.32	3.62
H_2O-	0.25	0.24	0.33	0.30	0.29	0.21	0.27	0.47
Total	100.50	100.10	99.53	99.58	100.69	99.48	99.61	99.39

TABLE 8. (Continued)

No.	41	42	43	44
SiO_2	45.03	45.52	44.54	48.73
Al_2O_3	14.50	13.78	15.72	13.53
Fe_2O_3	4.76	5.38	3.23	5.77
FeO	8.24	9.28	7.50	5.28
MgO	6.74	5.89	6.33	6.51
CaO	9.41	8.99	10.96	12.01
Na_2O	2.76	3.26	2.04	2.40
K_2O	0.93	0.54	0.32	0.35
TiO_2	2.04	2.89	1.37	1.49
P_2O_5	0.18	0.24	0.13	0.11
MnO	0.19	0.29	0.19	0.33
H_2O+	4.87	3.80	7.09	2.72
H_2O-	0.22	0.23	0.32	0.33
Total	99.87	100.09	99.74	99.56

The specimens of 1 to 6 belong to zone B and the rest to zone C.

* analyzed by A. MINAMI

TABLE 9. CHEMICAL COMPOSITIONS OF BASIC SCHISTS COLLECTED FROM THE DRILL CORE (No. 189) OF THE KAWAYAMA MINE ANALYST: Y. NISHIMURA

Spec. No.	1	2	3	4	5	6	7	8
SiO_2	48.11	49.86	45.11	39.69	49.58	50.25	49.44	44.80
Al_2O_3	17.03	16.46	13.28	16.21	16.14	16.49	17.39	17.34
Fe_2O_3	1.11	4.44	1.97	6.26	6.21	8.27	1.46	1.05
FeO	9.81	6.46	8.44	9.69	5.42	4.03	10.94	13.77
MgO	4.38	3.70	5.70	8.70	4.19	2.61	1.75	2.33
CaO	4.95	6.48	9.34	4.69	5.36	3.78	4.25	4.61
Na_2O	3.87	4.91	2.93	3.26	5.84	5.48	6.05	2.11
K_2O	1.48	0.41	0.19	1.11	0.79	2.19	0.90	2.93
TiO_2	1.73	1.97	3.85	3.02	2.58	2.44	2.76	2.91
P_2O_5	0.21	0.55	0.43	0.47	0.31	0.68	0.60	0.84
MnO	0.28	0.22	0.23	0.47	0.16	0.19	0.20	0.29
H_2O+	6.45	3.86	8.05	6.15	3.53	3.70	4.32	6.58
H_2O-	0.24	0.27	0.21	0.21	0.15	0.14	0.29	0.16
Total	99.65	99.59	99.73	99.93	100.26	100.25	100.35	99.72

TABLE 9. (Continued)

Spec. No.	9	10	11	13	14	15	16	17
SiO_2	40.50	48.10	40.11	43.41	38.59	44.42	47.58	43.76
Al_2O_3	18.83	17.22	18.74	13.82	14.95	13.24	14.41	16.29
Fe_2O_3	5.54	6.80	7.92	1.60	7.00	5.77	5.02	4.69
FeO	8.28	7.63	7.22	12.05	12.35	9.29	7.99	8.96
MgO	2.39	1.75	2.67	5.10	4.04	6.88	5.75	5.70
CaO	9.70	4.05	7.93	9.04	10.06	8.97	8.63	9.16
Na_2O	2.17	5.44	1.39	1.79	1.46	2.95	3.78	2.56
K_2O	2.92	1.76	4.79	0.41	0.68	0.29	0.54	0.58
TiO_2	4.03	2.63	3.58	2.14	3.38	2.04	1.93	2.04
P_2O_5	0.61	0.50	0.56	0.23	0.25	0.18	0.25	0.21
MnO	0.27	0.18	0.23	0.24	0.40	0.26	0.20	0.22
H_2O+	4.58	3.38	4.50	9.58	6.18	4.81	3.72	5.51
H_2O-	0.14	0.14	0.20	0.20	0.49	0.29	0.19	0.22
Total	99.96	99.58	99.84	99.61	99.83	99.39	99.99	99.90

TABLE 9. (Continued)

Spec. No.	18	19	20	21	22	25	26	27
SiO_2	43.34	51.22	43.52	47.07	45.83	49.03	50.15	45.45
Al_2O_3	14.42	12.30	13.90	14.70	14.02	14.31	15.01	16.97
Fe_2O_3	2.49	0.80	7.34	3.44	5.37	2.65	3.55	6.95
FeO	13.37	9.98	8.90	7.19	9.59	8.19	6.62	5.92
MgO	5.96	5.79	5.26	5.90	7.42	8.13	5.51	4.04
CaO	8.16	6.80	7.85	9.71	7.37	6.31	9.54	9.86
Na_2O	2.22	0.13	3.22	3.64	1.50	4.05	4.23	2.31
K_2O	0.45	2.19	1.33	0.54	0.23	0.29	0.14	1.85
TiO_2	2.35	1.04	3.34	1.47	2.56	1.45	1.82	1.74
P_2O_5	0.24	0.11	0.43	0.17	0.23	0.11	0.15	0.22
MnO	0.33	0.35	0.28	0.19	0.22	0.19	0.17	0.26
H_2O+	5.91	9.45	4.33	5.61	5.69	4.71	2.83	4.23
H_2O-	0.66	0.21	0.25	0.21	0.22	0.26	0.12	0.21
Total	99.90	100.37	99.95	99.84	100.25	99.68	99.84	100.01

TABLE 9. (Continued)

Spec. No.	28	29	31	32	35	38	39
SiO_2	48.60	48.32	46.30	50.68	46.15	45.27	46.78
Al_2O_3	12.72	13.96	17.96	15.42	14.47	15.37	13.71
Fe_2O_3	3.88	3.97	6.92	2.09	5.11	3.76	1.57
FeO	7.59	7.98	5.25	6.85	7.22	9.57	11.06
MgO	5.98	6.02	4.12	6.84	6.31	4.91	5.91
CaO	11.10	9.99	6.79	7.25	9.03	8.39	4.82
Na_2O	3.52	3.39	4.14	3.14	2.78	3.59	3.62
K_2O	0.46	0.32	1.54	2.48	1.16	0.53	0.73
TiO_2	1.46	1.91	2.34	1.36	1.82	2.21	2.22
P_2O_5	0.15	0.21	0.60	0.13	0.17	0.22	0.21
MnO	0.18	0.11	0.17	0.15	0.23	0.33	0.15
H_2O+	3.83	3.46	3.60	3.42	5.20	5.38	8.43
H_2O-	0.13	0.15	0.09	0.15	0.23	0.21	0.36
Total	99.60	99.79	99.82	99.96	99.88	99.74	99.57

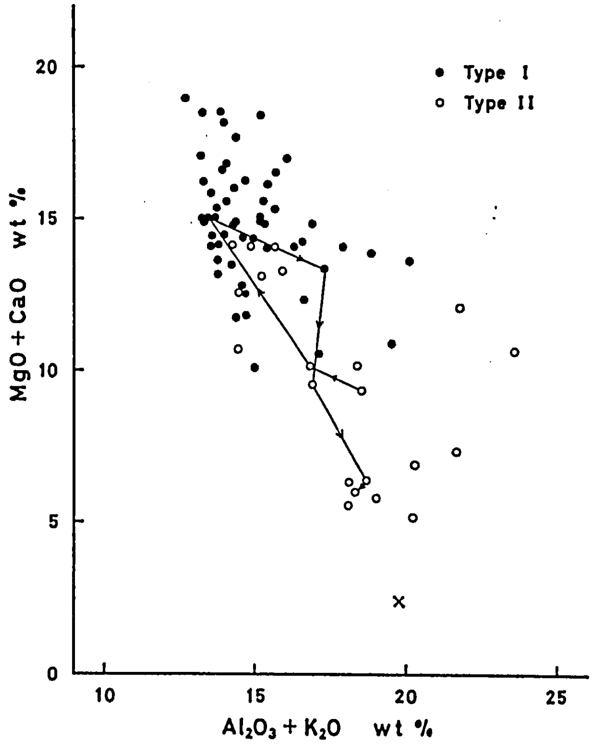


FIG. 20. ($MgO+CaO$)-($Al_2O_3+K_2O$) diagram for basic schists. Points linked by tie-lines with arrows indicate the basic schists selected from a basic schist mass about 25 m thick. The arrows show the descending order of the horizons of the specimens. The cross mark represents the average composition of 31 Paleozoic pelites from the Inner Zone of Southwest Japan after MIYASHIRO and HARAMURA (1962).

Inner Zone of Southwest Japan calculated by MIYASHIRO and HARAMURA (1962). As seen from the diagram, the more the core is approached from the margin, the more increases the content of ($MgO+CaO$) and decreases that of ($Al_2O_3+K_2O$). In other words, three specimens collected from the marginal zone are located on the direction toward the average pelitic rock from the field of basaltic composition, while two specimens representing the core part are basaltic, the rest being transitional. The zone with such peculiar composition ranges several to 8 m in thickness from the boundary to typical pelitic rocks. The origin of these type II rocks cannot be uniquely defined on the basis of chemical character only, but the author has the opinion that they represent some kind of hybrid zone formed either in the chilled margin of sill or in the altered pelites adjacent to the sill, heavily affected by selective migration of components at the time of intrusion in geosynclinal phase or during regional metamorphism.

On the other hand, main part of the basic mass, consisting of type I rocks, shows

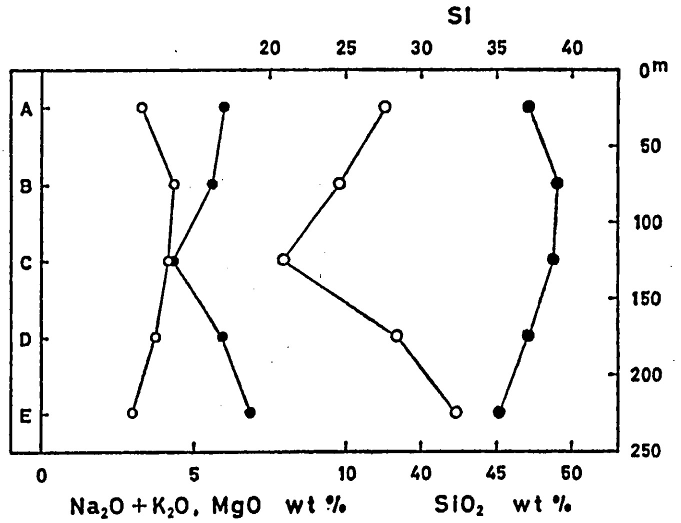


FIG. 21. Chemical variation for (Na_2O+K_2O), MgO, SiO_2 and SI of a larger basic schist mass, based on the average values against the horizon within the mass. Symbols are as follows: Small open circle $=(Na_2O+K_2O)$, Small solid circle=MgO, Large solid circle $=SiO_2$, Large open circle= SI, $SI=MgO\times100/(MgO+FeO+Fe_2O_3+Na_2O+K_2O)$.

a significant chemical variation according to the horizon in the basic mass. Average compositional variation against the horizon or height is shown in Fig. 21. Amounts of SiO_2 and of (Na_2O+K_2O) increase from the lower to the central part and decrease in proceeding to the upper part. On the contrary, amount of MgO and the solidification index (after KUNO et al., 1957) decrease both from the lower and the upper parts to the central region. These regular features of chemical variation are not in accordance with those of basic sills showing gravitational differentiation of magma, but would suggest something like selective migration of certain elements occurring either just after the emplacement or during the regional metamorphism.

It is an important, though difficult, problem to determine to what kind of igneous rock series the original rocks of such metamorphic rocks as greenschists or glaucophane schists belong, when they were intruded under geosynclinal condition before regional metamorphism. Two ways of approach are conceivable in this investigation. The one is to examine the bulk chemical composition of these rocks and the other is to investigate relic minerals such as pyroxenes.

The diagram of total alkali–silica relation has been proved to be useful to illustrate the difference in chemical composition between the tholeiitic and alkalic rock series (KUNO, 1959; MACDONALD and KATSURA, 1964). The same diagram for basic metamorphic rocks in the present district is shown in Fig. 22. The straight line in the diagram represents the boundary between the tholeiitic and alkalic fields in Hawaiian basaltic rocks after MACDONALD and KATSURA (1964). In the diagram,

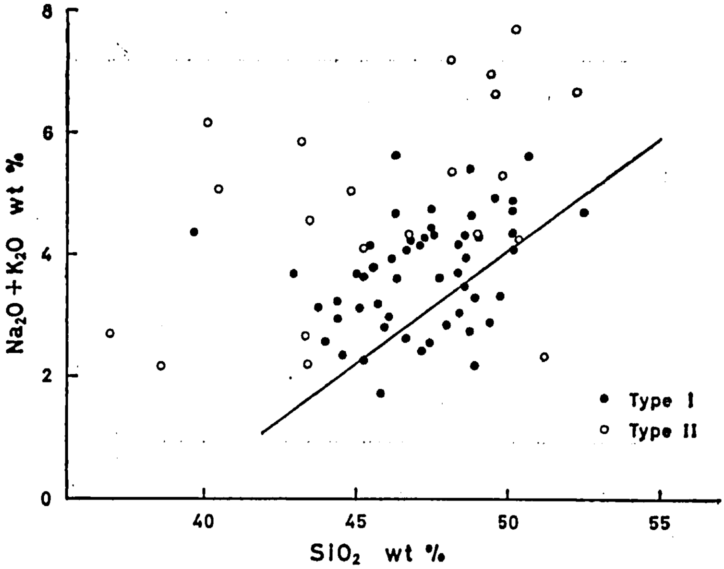


FIG. 22. Alkali-silica diagram for basic schists. The straight line is the boundary between the tholeiitic and alkalic fields of the Hawaiian lavas after MACDONALD and KATSURA (1964).

points plotted for all analyzed rocks of type I are distributed on both fields, but the majority of them fall on the field of the alkalic rocks. The rocks of type II are more dispersed and higher in alkali content than those of type I. Silica index θ as defined by SUGIMURA (1959, 1960) indicates how siliceous the parental magma of the volcanic rock is. The index θ of type I rocks in this district was calculated from the chemical composition recalculated to 100 percent except H_2O. It ranges from 39 to 21, the value also suggesting the basic rocks of type I to be alkalic.

Relic clinopyroxenes have been found sometimes in weakly recrystallized rocks both of type I and type II of zone B. Chemical compositions estimated from their optical properties are plotted on the Di-Hd-Fs-En trapezoid (Fig. 23) after the diagrams of WINCHELL and WINCHELL (1951) and DEER et al. (1963), along with some trends of clinopyroxene crystallization in igneous rocks for comparison. The minerals in question are augite close to salite after the nomenclature of POLDERVAART and HESS (1951), characteristic of basic alkalic rocks (MURRAY, 1954; WILKINSON, 1956, 1957; KUSHIRO, 1964).

Therefore, from these chemical as well as mineralogical features, it may be concluded that the majority of basic metamorphic rocks of the Nishiki-chô district have been derived from rocks of the alkalic rock series.

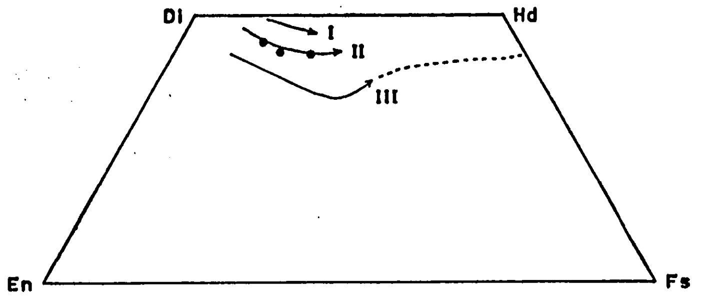


Fig. 23. Chemical compositions of relic clinopyroxenes in basic schists compared with some trends of clinopyroxene crystallization.
Solid circles: Clinopyroxenes in basic schists from the Nishiki-chô district (after NISHIMURA, 1971).
I : Trend in the Black Jack sill (WILKINSON, 1957).
II : Trend in the Garbh Eilean sill (MURRAY, 1954).
III: Trend in the Skaergaard intrusion (BROWN, 1957; BROWN and VINCENT, 1963).

B. Bulk Chemistry on Metamorphic Mineral Assemblages

1. *Chemical relation between metamorphic rocks of different zones*

In making zonal classification of a metamorphic terrain, mineral assemblage of isochemical series of rocks should be taken as its basis. It is, however, not always possible to chose precisely isochemical series of rocks throughout a wide region. The present Nishiki-chô district, as previously described, is divided into three zones on the basis of mineralogical changes of basic metamorphic rocks. While basic metamorphic rocks universally occur in zones B and C, the rocks are rare in zone A and available chemical data have not been obtained yet in this zone.

Chemical compositions of the basic metamorphic rocks of zones B and C are plotted on the ACF and the MgO-(FeO+Fe_2O_3)-(Na_2O+K_2O) diagrams (Figs. 24 and 25). As seen from these diagrams, fields of the rocks in these zones do not show any systematic difference from zone to zone but can be regarded to be approximately similar to one another. Furthermore, both diagrams demonstrate that the basic metamorphic rocks from the present district and from other glaucophanitic terrains (e. g., California, New Caledonia and Shikoku) are also essentially the same with regard to ACF and MgO-(FeO+Fe_2O_3)-(Na_2O+K_2O) proportions (COLEMAN, 1967; ERNST et al., 1970).

Accordingly, it can be presumed that the mineralogic difference of basic metamorphic rocks in different zones as well as in different terrains reflects the difference in physical condition of metamorphism.

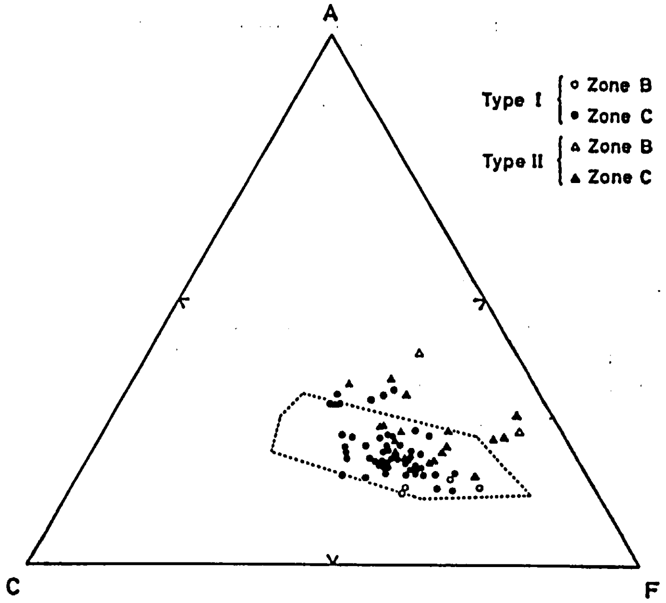


FIG. 24. ACF diagram for basic schists from zones B and C. The area designated by the dotted line indicates the compositional range of analyzed basic metamorphic rocks from California and New Caledonia (COLEMAN, 1967).

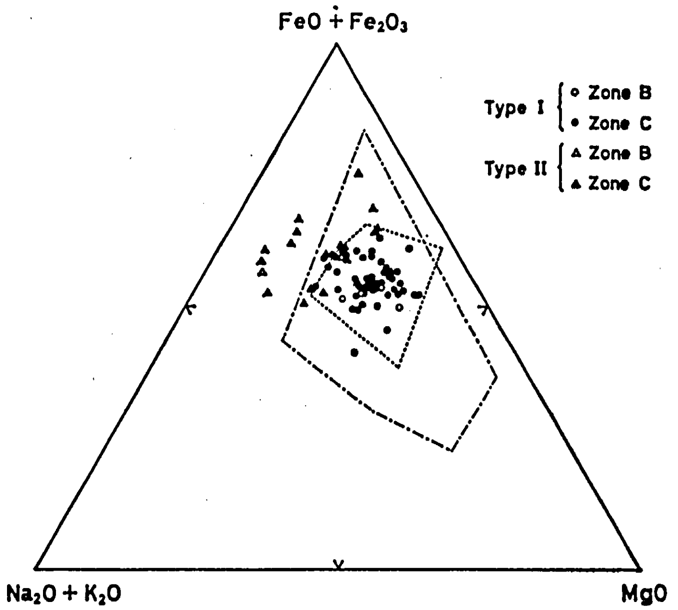


FIG. 25. MFA diagram for basic schists from zones B and C. The areas designated by the dotted and the broken lines indicate the compositional ranges of analyzed basic metamorphic rocks from Shikoku and California, respectively (ERNST et al., 1970).

2. *Chemical control on the formation of amphiboles*

The basic metamorphic rocks of zone C in the Nishiki-chô district are mainly divided into three categories with regard to the kind of amphiboles, namely, actinolite-epidote-chlorite, subcalcic hornblende-epidote-chlorite and glaucophane-epidote-chlorite. These are named tentatively actinolite schist, subcalcic hornblende schist and glaucophane schist, respectively. Schists with different kind of amphiboles occur interlayered on the same horizon, indifferently to the metamorphic zoning. Accordingly, these schists with different kind of amphiboles cannot be assumed to relate to the difference in physical condition, but can be regarded to reflect some different chemical conditions.

Relations between the mineral assemblage and bulk chemical composition of the basic rocks are examined in some diagrams for this purpose. In the MgO–($FeO+Fe_2O_3$)–(Na_2O+K_2O) diagram (Fig. 26), glaucophane schists are plotted on the field of richer side in total iron and of poor side in magnesia against total alkali content, while actinolite schists occupy the field of poorer side in total iron and of richer side in magnesia. Subcalcic hornblende schists fall on the intermediate field of above two ones. In the Al_2O_3–Na_2O–CaO diagram too (Fig. 27), although three categories of basic schists are fairly mixed, it seems that subcalcic hornblende schists occupy a rather intermediate field between actinolite schists and glaucophane schists. As seen from both diagrams, it is rather evident that excess of alkali does not play

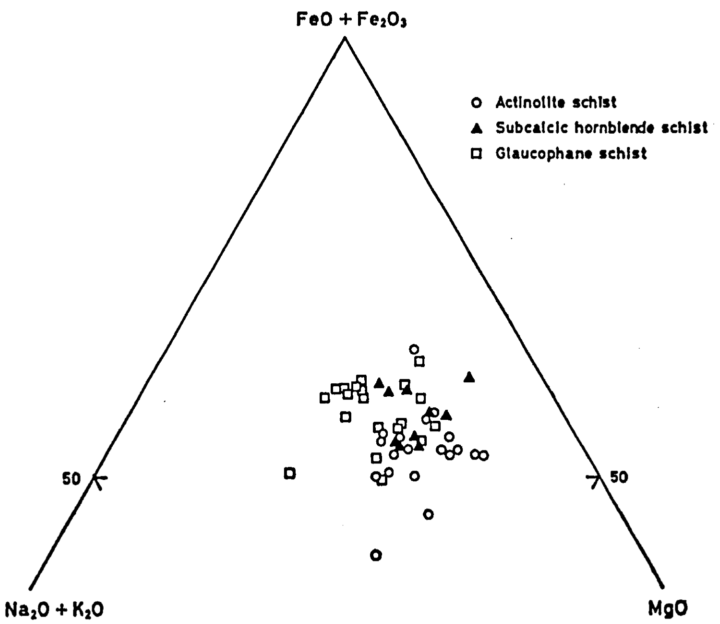


FIG. 26. MFA diagram showing chemical variation of actinolite schists, subcalcic hornblende schists and glaucophane schists of zone C.

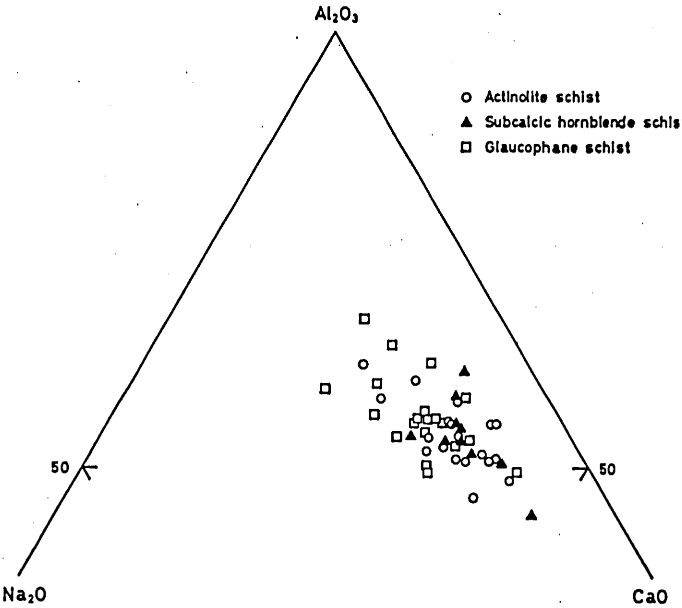


FIG. 27. Al_2O_3-Na_2O-CaO diagram showing chemical variation of actinolite schists, subcalcic hornblende schists and glaucophane schists of zone C.

any significant role for the formation of glaucophane.

The most distinct differences between these three categories of basic schists can be read from the diagram (Fig. 28) showing the relation of FeO and Fe_2O_3. That is, the diagram illustrates that glaucophane schists reflect higher Fe_2O_3/FeO conoition, while actinolite schists indicate lower Fe_2O_3/FeO condition or rather lower in total iron content, and that subcalcic hornblende schists are moderate in Fe_2O_3/FeO ratio. High value of Fe_2O_3/FeO ratio may probably due to high oxygen pressure during metamorphism. These features are in harmony with the facts that epidotes in glaucophane schists have smaller optical angle $2V_X$ than those in glaucophane-free schists and that chlorites in glaucophane schists are deeper in green color than those in glaucophane-free schists, as described in the preceding chapter. Furthermore, high oxidation ratio would favor to form alkali amphibole having an appreciable amount of riebeckite molecule. In this context it is to be noted that alkali amphiboles produced under such conditions in the present district are all normal symmetric (b=Z) as far as examined in this study (see Fig. 16).

It has been pointed out in the Sambagawa metamorphic belt by some workers (SEKI, 1958; IWASAKI, 1963; BANNO, 1964; ERNST et al., 1970) that bulk compositions of glaucophane schists have relatively high oxidation ratio as compared with those of intimately associated glaucophane-free schists. More than half of alkali amphiboles from the Sambagawa basic schists are also normal symmetric. On the other hand, basic Franciscan metaigneous rocks showing almost any value

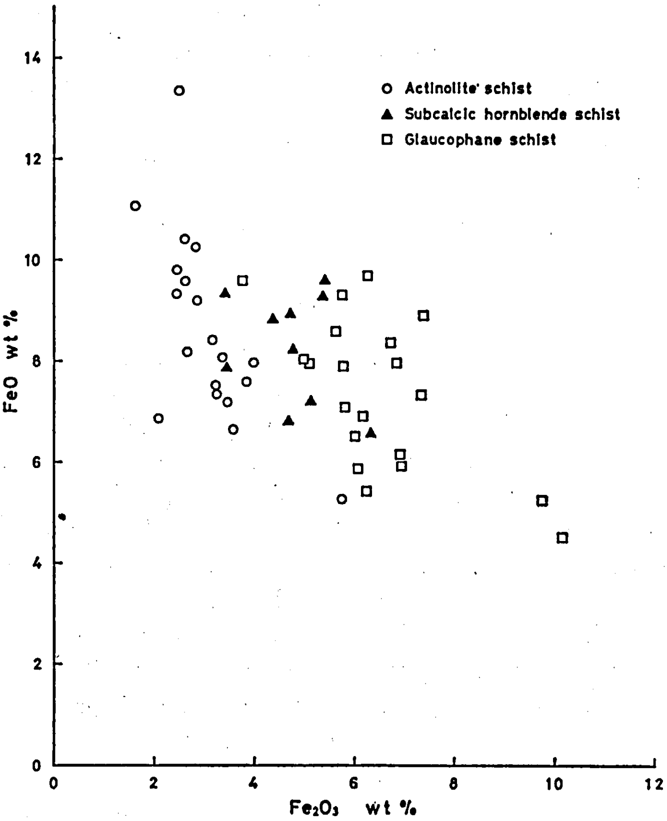


FIG. 28. FeO-Fe_2O_3 diagram showing oxidation ratio for actinolite schists, subcalcic hornblende schists and glaucophane schists of zone C.

of oxidation ratio include alkali amphiboles, almost all of which are parallel symmetric (b=Y) (ERNST et al., 1970).

The metamorphic environment of the California Coast Ranges demonstrates the physical condition appropriate to the typical glaucophane-schist facies, whereas in the Sambagawa belt and in the Sangun belt, to which the present district belongs, physical conditions must have been transitional between those of the typical glaucophane-schist facies and the greenschist facies, as will be discussed later. Accordingly, as to basic metamorphic rocks, the relation between the formation of alkali amphiboles and the oxidation ratio of the host rocks and the range of composition in alkali amphiboles are a function of the attending physical condition.

V. GENERAL CONSIDERATION ON METAMORPHISM

With the progress of study of metamorphic terrains it is becoming clear that metamorphic features vary more or less from terrain to terrain within the same metamorphic belt or the same metamorphic facies. In such cases, the concept of metamorphic facies plays a role as a standard scale to distinguish the individuality of each metamorphic terrain, which would enrich our knowledge about real features of the metamorphic belt.

In this chapter, the author intends to clarify the nature of metamorphism of the Nishiki-chô district by considering the data given in the preceding chapters and by comparing the mineral paragenesis and the chemistry of rocks of this district with those of some other terrains.

A. PREHNITE-PUMPELLYITE METAGREYWACKE FACIES

On the basis of geological and petrological studies of some Triasic sediments from the New Zealand geosyncline (COOMBS, 1954), COOMBS (1960, 1961) and COOMBS et al. (1959) proposed two new metamorphic facies, namely, the zeolite facies and the prehnite-pumpellyite metagreywacke facies. The former was defined "to include at least all those assemblages produced under physical conditions in which the following are commonly formed: quartz-analcime, quartz-heulandite, quartz-laumontite" (COOMBS et al., 1959), representing the lowest grade metamorphic condition. The latter was defined "to include those assemblages produced under physical conditions in which the following are commonly formed: quartz-prehnite-chlorite or quartz-albite-pumpellyite-chlorite, without zeolites and without the characteristic minerals of the glaucophane schist facies, jadeite or lawsonite" (COOMBS, 1960), and the facies bridges the gap between the zeolite facies and the greenschist or the glaucophane-schist facies. Moreover, COOMBS (1960) distinguished two zones in the prehnite-pumpellyite metagreywacke facies:

(1) A lower grade quartz-prehnite zone in which some combination of the following is found: quartz, albite, prehnite, pumpellyite, chlorite, calcite, sphene, orthoclase, muscovite.

(2) A higher grade zone with some combination of quartz, albite, chlorite, sphene, actinolite, muscovite, calcite, stilpnomelane, pumpellyite and epidote.

Zone A characterized by the pumpellyite-chlorite assemblage, which is associated neither with prehnite nor actinolite, represents the lowest grade part of the metamorphic system of the Nishiki-chô district. Stilpnomelane is found also sporadically in this zone. The zone grades into zone B characterized by the pumpellyite-actinolite assemblage with increasing grade of metamorphism. Similar rocks with the assemblage pumpellyite-chlorite has been found in the Franciscan belt (SEKI, 1969; ERNST et al., 1970), the Kanto Mountains (SEKI, 1961, 1969), the Tanba Plateau (HASHIMOTO and SAITO, 1970) and the Chichibu belt (HASHIMOTO and KASHIMA, 1970). Rocks in the former two cases grade into those of the glaucophane-schist facies with increasing grade of metamorphism, while in the latter two cases into those of the greenschist facies.

The pumpellyite-actinolite assemblage characterizing zone B is associated with stilpnomelane and rarely with epidote but neither with prehnite nor such minerals as characterizing the glaucophane-schist facies. The zone grades into zone C characterized by the epidote-glaucophane assemblage or the epidote-subcalcic hornblende assemblage. The pumpellyite-actinolite assemblage would correspond to the higher grade part of the prehnite-pumpellyite metagreywacke facies (COOMBS, 1960, 1961), or to the pumpellyite-actinolite facies as defined by HASHIMOTO (1966). The similar assemblage has been described in many parts of the Wakatipu metamorphic belt (COOMBS, 1960, 1961; COOMBS et al., 1959; LANDIS and COOMBS, 1967), in the central part of Kii Peninsla of the Sambagawa metamorphic belt (SEKI et al., 1964) and in the Asahi-chô area of the Sangun metamorphic belt (HASHIMOTO, 1968b). This assemblage grades either into the greenschist facies (e. g., in the Wakatipu metamorphic belt and in Kii Peninsla) or into the glaucophane-schist facies (e. g., in the Asahi-chô area) with increasing grade of metamorphism. Zone B of the Nishiki-chô district corresponds to the latter case.

On the other hand, the prehnite-pumpellyite assemblage without actinolite, which represents the lower grade zone of the prehnite-pumpellyite metagreywacke facies defined by COOMBS, has not been found in the Nishiki-chô district. This assemblage occurs mainly in the lower grade part of non-glaucophanitic metamorphic terrains such as the Wakatipu metamorphic belt, the central part of Kii Peninsla of the Sambagawa belt, the eastern Akaishi Mountains (MATSUDA and KURIYAGAWA, 1965) and the Tanzawa Mountains (SEKI et al., 1969). The former two cases grade into the pumpellyite-actinolite assemblage with increasing grade of metamorphism, while the latter two cases grade directly into the greenschist facies. HASHIMOTO (1968a) emphasized that the prehnite-pumpellyite assemblage proceeds to the glaucophane-schist facies zone with increasing grade of metamorphism in the Katsuyama district of the Sangun metamorphic belt. This case, however, seems to be very rare.

Therefore, the lower grade metamorphic facies, roughly corresponding to the prehnite-pumpellyite metagreywacke facies, consists of three diagnostic mineral assemblages, namely, prehnite-pumpellyite, pumpellyite-chlorite and pumpellyite-actinolite. Each assemblage or series of assemblages would be a good parameter of physical conditions, particulaly pressure, that prevailed in metamorphism. In this regard, SEKI (1969) proposed a scheme of classification of facies series in low-grade metamorphism, though there remain some problems as to the pumpellyite-chlorite and the pumpellyite-actinolite assemblages. Judging from the above descripion, the series of the pumpellyite-chlorite to the pumpellyite-actinolite assemblage in the Nishiki-chô district seems to represent relatively high pressure condition of metamorphism.

B. GLAUCOPHANE-SCHIST FACIES

ESKOLA (1939) defined the glaucophane-schist facies as a specified range of physical condition favorable for the formation of glaucophane and lawsonite. Subsequently, many geologists discussed the physical and chemical conditions which govern the formation of glaucophane schists. One group of geologists believes that many glaucophane schists were formed under a peculiar chemical condition during metamorphism, especially in response to metasomatism effected by sodic pore fluide (e. g., TALIAFERRO, 1943; BROTHERS, 1954). The other group considers that glaucophane schists must be formed under a certain range of physical condition characterized by low to moderate temperature and relatively elevated pressure (DE ROEVER, 1955a, 1955b; MIYASHIRO and BANNO, 1958; ERNST, 1963; COLEMAN and LEE, 1963).

The jadeite-quartz assemblage and/or arragonite are found in rocks of the glaucophane-schist facies (DE ROEVER, 1955b; BLOXAM, 1956; MCKEE, 1962; COLEMAN and LEE, 1962). It was experimentally proved that they are only stable under considerably high soild pressure at low to moderate temperature (BIRCH and LE COMTE, 1960; SIMMONS and BELL, 1963). MIYASHIRO (1965) redefined the glaucophane-schist facies to represent a definite range of physical condition favorable for the formation of glaucophane, and divided the facies into two cases. One is the typical glaucophane-schist facies, which contains such diagnostic minerals or mineral assemblage as jadeite-quartz, lawsonite and aragonite as well as glaucophane. This facies corresponds to the lawsonite-glaucophane-jadeite facies after WINKLER (1965) and to the glaucophane-lawsonite-schist facies after TURNER (1968). Another is presumed to be transitional between the typical glaucophane-schist facies and the greenschist facies. The mineral assemblages are closely similar to those of the epidote-glaucophane subfacies as formerly defined by MIYASHIRO and SEKI (1958a). WINKLER (1965) and TURNER (1968) placed these assemblages in the greenschist facies, transitional towards the typical glaucophane-schist facies, and proposed the glaucophanitic greenschist facies. However, there remain many ambiguous points as to the glaucophane-schist facies in the transitional sense.

Zone C of the Nishiki-chô district is characterized the appearance of either crossite or subcalcic hornblende and by the disappearance of pumpellyite in basic schists. Basic schists of this zone are divided into three categories with regard to the kind of amphiboles, namely, actinolite schist, subcalcic hornblende schist and glaucophane schist. As they occur intimately intercalated on the same horizon, these categories do not suggest different physical conditions, but must depend on some different chemical conditions, mainly the oxidation ratio, as shown in the previous chapter. Garnet also occurs in pelitic and siliceous schists in the higher grade part of zone C, whereas biotite does not appear in any rocks of this zone. These features of zone C in the present district do not suggest the physical condition either of the typical glaucophane-schist facies or the greenschist facies, but would represent a transitional one between them. According to the definition of MIYASHIRO (1965), however, this zone is also involved in the glaucophane-schist facies.

Recently, subcalcic hornblende, representing an intermediate composition between calcium amphiboles and alkali amphiboles, has been described from basic metamorphic rocks in the glaucophanitic metamorphic terrains, but it has not been found in any rocks of the non-glaucophanitic terrains. Subcalcic hornblende in question occurs stably under the same condition as the glaucophane schist not only in the present district but also in some other parts of the Sangun belt (SEKI, 1958; HASHIMOTO, 1968a, 1968b), the Sambagawa belt (SEKI, 1958; IWASAKI, 1963; BANNO, 1964; KANEHIRA, 1967; ERNST et al., 1970) and the Pennine zone (BEARTH, 1958; VAN DER PLAS, 1959), but under the typical glaucophane-schist facies such as in the California Coast Ranges this mineral does not occur commonly (LEE et al., 1966; HIMMELBELG and PAPIKE, 1969)[1]. The stability range of the mineral seems to be rather wide, probably ranging through two metamorphic facies, namely, the glaucophane-schist facies to the lower temperature part of the epidote amphibolite facies (transitional between the glaucophane-schist facies and the epidote amphibolite facies).

The former case may apply to zone C of the present district, zone III of the Kôtu–Bizan area (IWASAKI, 1963), zone B of the Bessi–Ino district (BANNO, 1964) and the lower grade part of zone C of the Iimori district (KANEHIRA, 1967). Under such condition, actinolite schist, subcalcic hornblende schist and glaucophane schist occur side by side in the same zone. Moreover, actinolite and subcalcic hornblende, or subcalcic hornblende and glaucophane can be found to coexist as separate grains on the same thin section as described in zone C of the Nishiki-chô district given in the preceding chapter (see Table 7).

While, the latter case may apply to zone IV of the Kôtu–Bizan area, zone C of the Bessi–Ino district, the higher grade part of zone C of the Iimori district, zone VI of the Kanto Mountains (SEKI, 1958) and the higher grade part of the chlorite zone of the Ômi district (SEKI, 1958). Under the condition of the latter case, that is higher in temperature than the former, actinolite schist and glaucophane schist may not occur as essential type of rocks, because actinolite and/or glaucophane would become unstable and react with epidote and chlorite to form subcalcic hornblende or common hornblende. Glaucophane schist, however, occurs very rarely in some terrains because of the difference in temperature of decomposition between actinolite and glaucophane. According to BANNO (1964), the boundary between the former and the latter conditions is represented by the following reaction.

$$\underset{\text{albite}}{8\,NaAlSi_3O_8} + \underset{\text{actinolite}}{6Ca_2(Mg_{4.5}Al_{0.5})(Al_{0.5}Si_{7.5})O_{22}(OH)_2}$$
$$+ \underset{\text{chlorite}}{Mg_5Al_2Si_3O_{10}(OH)_8} = \underset{\text{subcalcic hornblende}}{8\,Na_{0.5}(Na_{0.5}Ca_{1.5})(Mg_4Al)(AlSi_7)O_{22}(OH)_2}$$
$$+ \underset{\text{quartz}}{16\,SiO_2} + 14\,H_2O \quad \cdots\cdots (7)$$

Judging from these respects, at the lower temperature such as glaucophane-schist facies, subcalcic hornblende may have rather narrow compositional field and there

1) Subcalcic hornblende also occurs in eclogitic rocks (COLEMAN et al., 1965; BINNS, 1965; MORGAN, 1970 and others).

may be a miscibility gap between actinolite and subcalcic hornblende. Furthermore, the formation of the mineral is controled by slightly different bulk chemical composition of the host rocks as above discussed. With increasing temperature, the compositional field of the minerals may expand and the compositional variation from actinolite to subcalcic hornblende appears to be continuous suggested by Banno (1964) and Ernst et al. (1970).

Therefore, wide-spread occurrence of subcalcic hornblende in basic metamorphic rocks may probably be regarded as a characteristic feature of the glaucophane-schist facies. Accordingly, the glaucophane-schist facies, transitional between the typical glaucophane-schists facies and the greenschist facies, can be defined as such physical condition as to form the following mineral assemblages: chlorite-epidote-glaucophane (mainly normal symmetric one), chlorite-epidote-subcalcic hornblende or chlorite-epidote-glaucophane-subcalcic hornblende.

C. Metamorphism of the Nishiki-chô District

The metamorphic basement formations of the Nishiki-chô district can be divided into the following three zones in order of increasing metamorphic grade, as discussed in the preceding chapters:

Pumpellyite-chlorite zone of the prehnite-pumpellyite metagreywacke facies
Pumpellyite-actinolite zone of the prehnite-pumpellyite metagreywacke facies
Epidote-glaucophane zone and/or epidote-subcalcic hornblende zone of the glaucophane-schist facies

Boundary surfaces between these metamorphic zones are nearly parallel to the stratification and the metamorphic grade increases from the upper to the lower horizon of the stratigraphic succession. That is, the first zone corresponds to the Nishiki Group (Lower to Upper Permiam), and the second and third zones to the Tsuno Group (probably Carboniferous).

Moreover, as the result of structural analyses for the metamorphites, two phases of deformation have been detected in the present district. The earlier phase (L_1-phase) is represented by the formation of the lineation L_1 defined by the preferred orientation of prismatic metamorphic minerals as well as the intersection of S_1 and S_2. During this phase may have taken place progressive regional metamorphism grading through three zones mentioned above. The later phase (L_2-phase), which is characterized by the formation of the lineation L_2 shown as grooves on S_1, corresponds to the deformation related to the formation of major folds and the mechanical property of rocks was rather brittle. The tectonic slide, which runs along the boundary zone between the slightly metamorphosed rocks of the pumpellyite-chlorite zone and the schistose rocks of the pumpellyite-actinolite zone, is believed to have been simultaneous with the L_2-phase and presumably reactivated in later geologic ages.

Nureki (1969) laid stress on the facts that the crystalline schist formation in the

Chugoku province always lies under slightly metamorphosed Paleozoic formations and that between both formations there develops distinct tectonic discontinuity surface, and inferred that the crystalline schists have resulted from the Sangun metamorphism, by which the metamorphic zones higher than the pumpellyite-actinolite zone in grade have been formed, whereas the slightly metamorphosed rocks of Paleozoic formations, showing original clastic fabrics, are believed to have been altered to the prehnite-pumpellyite zone by the burial metamorphism of a later phase than the Sangun metamorphism.

It is, however, reasonable on the basis of structural, stratigraphic as well as petrological studies to believe that the metamorphites of those three zones mentioned above were formed by one and the same cycle of metamorphism, namely, the Sangun metamorphism. In other words, the Sangun metamorphism affected at least some parts of the "non-metamorphic" Paleozoic formations overlying the crystalline schist formation. Accordingly, the metamorphic facies series of the Sangun metamorphism of the Nishiki-chô district consists of the series: pumpellyite-chlorite zone—pumpellyite-actinolite zone—epidote-glaucophane zone and/or epidote-subcalcic hornblende zone, and corresponds to the high-pressure intermediate group in the sense of MIYASHIRO (1961).

APPENDIX

Mineral assemblages and optical properties of constituent minerals of the analyzed basic schists are shown in the following (Table 10). The localities of these rocks are shown in Figs. 29 and 30. The correlation between the numbers given in Table 8 and in Fig. 29 and the specimen numbers of the analyzed rocks are given in Table 10.

TABLE 10. PETROGRAPHIC DESCRIPTION OF ANALYZED ROCKS

No.	Spec. No.	Type	Min. Ass.	Amphiboles Var.	α	β	γ	2Vx	Chlorite β	±	Epidote 2Vx	Albite 2Vz
1	391031-1	I	P-A	act			1.657	75°	1.630	−		
2	69318-1*	I	P-A									
3	6656-2	II	E-C									
4	6656-4	II	E-C						1.654	−		
5	69326-10	I	P-A	act			1.655	74°	1.627	−	72°	
6	661022-6	I	P-A									
7	3927-13	II	E-C						1.644	−		
8	6655-2	I	E-C								70°	75°
9	6655-3	I	G-C	gl	1.639	1.662	1.669	40°	1.629	−	71°	76°
10	38520-5	I	G-C	gl	1.646	1.660	1.669	49°	1.622	+	70°	76°
11	6655-4	I	G-C	gl	1.634	1.659	1.665	34°	1.620	+	70°	76°
12	3886-5	I	G-C	gl	1.648	1.669	1.672	76°	1.623	+	69°	76°
13	6655-6	I	G-C								68°	75°
14	6655-7	I	A-C								70°	75°
15	6655-15	I	S-C	shr	1.633	1.652	1.660	54°	1.619	+	72°	75°
16	38513-6	I	G-C	gl act	1.645 1.631	1.671 1.654	1.673 1.661	49° 66°	1.629	−	70°	76°
17	6655-17	I	S-C	shr	1.641	1.660	1.667	57°	1.630	−	73°	77°
18	6655-18	I	E-C								72°	75°
19	381225-1	I	E-C						1.622	+	74°	77°
20	38729-11	II	E-C						1.639	−	72°	
21	6657-1	I	G-C	gl act	1.643 1.633	1.663 1.653	1.668 1.661	37° 63°	1.624	+	71°	77°
22	6657-2	I	S-C	shr			1.666	45°	1.629	+	71°	74°
23	6657-3	I	E-C								71°	
24	6657-4	I	A-C	act			1.659	71°	1.626	+	77°	
25	391011-1	I	S-C	shr act			1.665 1.658	59° 69°	1.629	−	74°	76°
26	381221-8	I	G-C	gl	1.640	1.663	1.668	42°	1.616	+	68°	78°
27	6655-12	I	G-C	gl			1.674	73°	1.629	−	69°	
28	6655-11	I	A-C	act			1.655	73°	1.622	+	80°	
29	6655-13	I	A-C	act			1.661	68°	1.629	−	74°	77°
30	3885-7	I	A-C						1.627	−	76°	78°
31	38730-1	I	A-C	act	1.638	1.655	1.661	68°	1.630	−	75°	77°
32	6655-9	I	S-C	shr	1.638	1.658	1.664	60°	1.629	+	73°	75°
33	6656-5	II	E-C						1.643	−	79°	
34	38729-1	I	G-C	gl	1.648	1.661	1.669	51°	1.620	+	71°	77°
35	6656-8	I	G-C	gl	1.649	1.664	1.669	69°	1.617	+	69°	75°
36	6656-9	I	G-C	gl		1.663	1.670	64°	1.625	+	71°	75°
37	6656-10	I	G-C	gl	1.641	1.670	1.673	68°	1.623	+	70°	77°
38	6656-16	I	A-C	act	1.626	1.641	1.653	74°	1.621	+	74°	
39	6656-17	I	A-C	act			1.653	74°	1.621	+	74°	
40	661019-2	I	A-C	act			1.658	70°	1.627	−	71°	
41	661019-4	I	S-C	shr act	1.633	1.652	1.660	54° 63°	1.623	+	71°	77°

TABLE 10. (Continued)

No.	Spec. No.	Type	Min. Ass.	Amphiboles Var.	α	β	γ	$2V_X$	Chlorite β	$\pm$	Epidote $2V_X$	Albite $2V_Z$
42	661021-10	I	S-C	shr			1.667	54°	1.633	−		
43	661023-1	I	A-C									
44	KH 14-175	I	A-C	act			1.656	72°	1.620	+	72°	
	189-1	II	E-C						1.634	−		
	189-2	II	E-C						1.629	−		
	189-3	I	E-C									
	189-4	I	G-C	gl	1.651	1.665	1.670	68°	1.621	+	68°	
	189-5	II	G-C	gl act			1.673	68° 68°	1.621	+	69°	
	189-6	II	E-C									
	189-7	II	E-C						1.657	−		
	189-8	II	E-C						1.656	−		
	189-9	II	E-C						1.650	−		
	189-10	II	E-C						1.651	−		
	189-11	II	E-C						1.641	−		
	189-13	II	E-C						1.636	−		
	189-14	II	E-C									
	189-15	I	G-C	gl	1.644	1.664	1.669	35°	1.624	+	70°	
	189-16	I	G-C	gl			1.670	36°	1.625	+	70°	
	189-17	I	S-C	shr			1.665	43°	1.628	+	70°	75°
	189-18	II	A-C	act			1.660	71°	1.633	−		
	189-19	II	E-C									
	189-20	II	G-C	gl act			1.675 1.658	48° 67°	1.624	+	69°	
	189-21	I	A-C	act			1.655	69°	1.621	+		
	189-22	I	S-C	shr			1.661	58°	1.621	+	70°	75°
	189-25	I	A-C	act			1.654	66°	1.620	+		
	189-26	I	A-C	act			1.658	70°	1.626	+		
	189-27	I	G-C	gl			1.672	47°	1.625	+	70°	75°
	189-28	I	A-C	act			1.661	65°	1.629	−	70°	75°
	189-29	I	A-C	act			1.661	66°	1.630	−		
	189-31	I	E-C									
	189-32	I	A-C	act			1.653	74°	1.620	+	74°	
	189-35	I	S-C	shr			1.661	43°	1.620	+	71°	77°
	189-38	II	G-C	gl			1.676	45°	1.631	−	69°	
	189-39	II	A-C						1.631	−		

* Relic clinopyroxene is observed in the rock. Optical properties of the mineral are as follows: $\alpha=1.680$, $\beta=1.689$, $\gamma=1.710$, $2V_Z=53°$.

P-A = pumpellyite-actinolite assemblage
E-C = epidote-chlorite assemblage
A-C = actinolite-epidote-chlorite assemblage
S-C = subcalcic hornblende-epidote-chlorite assemblage
G-C = glaucophane-epidote-chlorite assemblage

act = actinolite
shr = subcalcic hornblende
gl = glaucophane (crossite)
± = optic sign

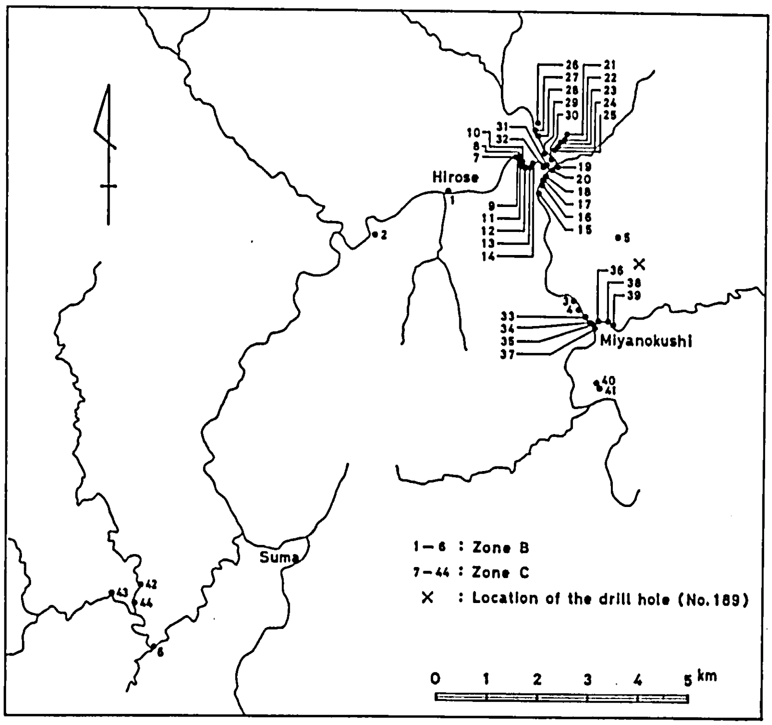


FIG. 29. Locality map of the analyzed specimens collected on the field. The data are listed in Table 8.

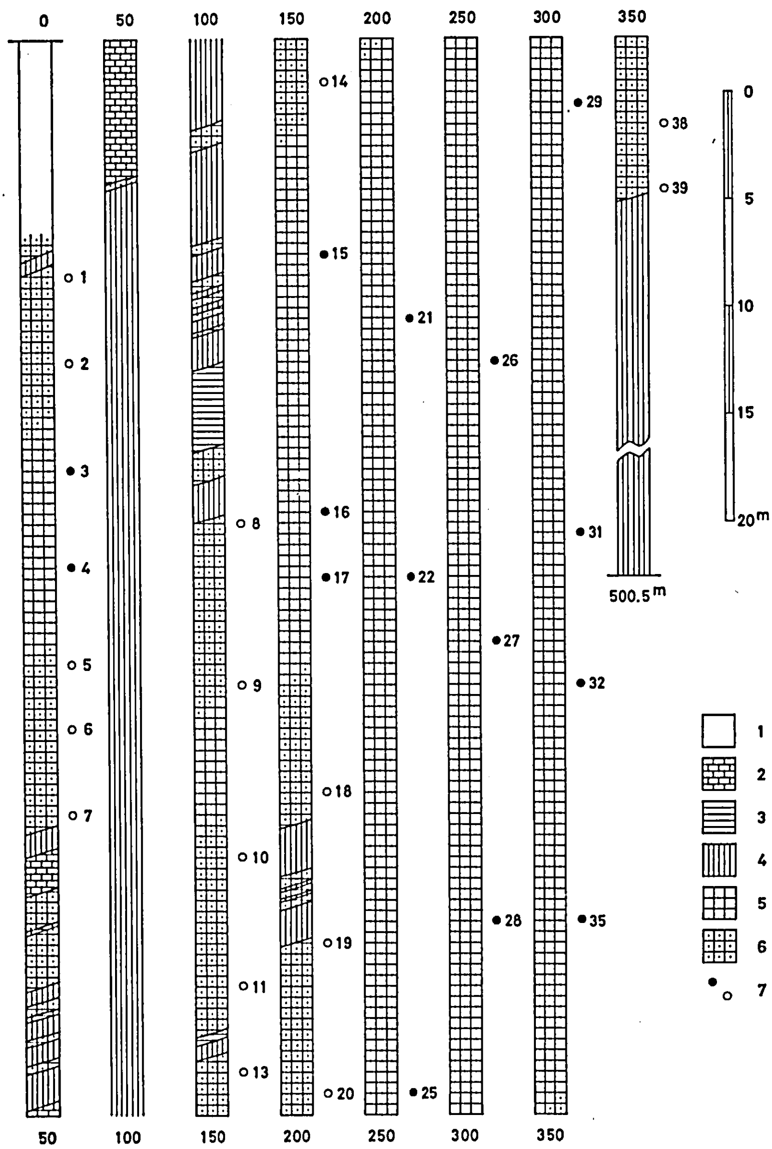


FIG. 30. Columnar section of the drill core (No. 189) of the Kawayama Mine, showing the positions of the analyzed specimens. The location of the drill hole (No. 189) is shown in Fig. 29. The analyzed data are listed in Table 9.
1: Surface soil, 2: Calcareous schists, 3: Siliceous schists, 4: Pelitic schists,
5: Basic schists of type I, 6: Basic schists of type II, 7: Analyzed specimens.

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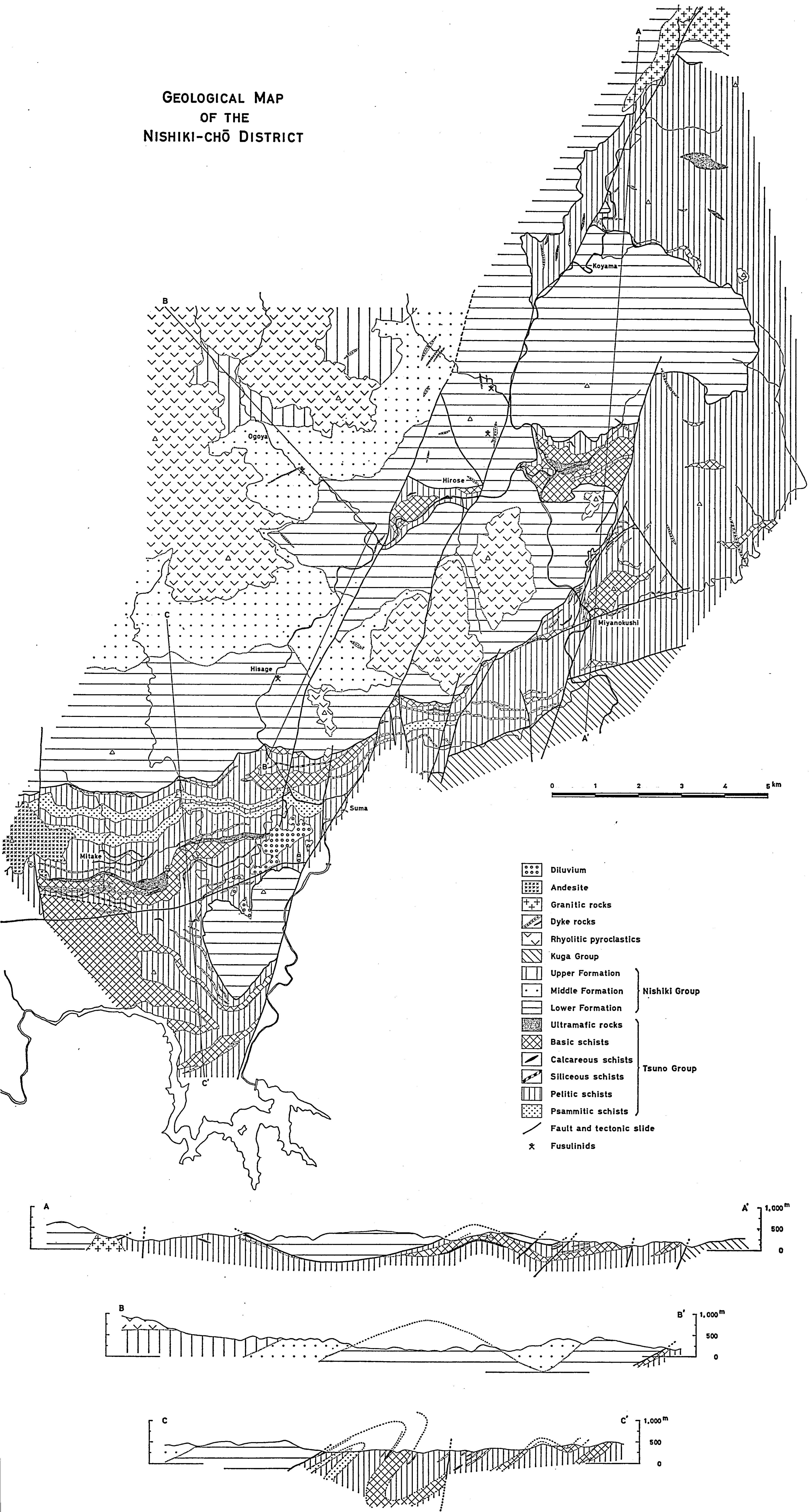
GEOLOGICAL MAP
OF THE
NISHIKI-CHŌ DISTRICT
A
B
C
A'
B'
C'
Koyama
Ogoya
Hirose
Miyanokushi
Hisage
Suma
Mitake
0 1 2 3 4 5 km
Diluvium
Andesite
Granitic rocks
Dyke rocks
Rhyolitic pyroclastics
Kuga Group
Upper Formation
Middle Formation
Lower Formation
Nishiki Group
Ultramafic rocks
Basic schists
Calcareous schists
Siliceous schists
Pelitic schists
Psammitic schists
Tsuno Group
Fault and tectonic slide
Fusulinids
1,000m
500
0